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HYDROLOGY IN RELATION TO ECONOMIC GEOLOGY.[1]

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THE SCOPE OF GEOLOGY.

GEOLOGY is the premier earth science. It is concerned with the rocks that form the crust of the earth—their character, structure, origin, and utilization, and the physical history of the earth and history of life on the earth to the extent that these can be determined from the character and structure of the rocks and the fossils they contain. Under the term rock, however, geologists include the incoherent materials that mantle the consolidated rocks. Geology uses the basic sciences, physics, chemistry, and biology, as its tools, but in doing so it has developed a distinctive technique and subject matter.

Etymologically, the term geology would include all of geophysics, geochemistry, and geobiology. Actually the geologists have limited their science to a more restricted and distinctive field. Thus geophysics, in the broad sense in which the term is used in the American Geophysical Union, includes meteorology, hydrology, oceanography, seismology, terrestrial magnetism and electricity, geodesy, and tectonophysics. Geology lays claim to only a part of this field. It is concerned with these subjects only in so far as they are applicable to the rocks that form the crust of the earth.

The limitation of geology to the earth's crust is doubtless wise in that it maintains the integrity and effectiveness of the science. However it is im-

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portant that we should cultivate thoroughly all phases of the study of the earth's crust, even though they may involve new methods requiring increased application of physics and chemistry. It appears that if geology is to hold its position of usefulness in its distinctive field it must keep up with the march of science by more thorough training of geologists in the basic and related subjects.

THE SCOPE OF HYDROLOGY.

Hydrology is one of the earth sciences. It is concerned with the water of the earth, its physical and chemical reactions with the rest of the earth, and its relation to the life of the earth. It uses the basic sciences and geology, but, like geology, it is developing distinctive subject matter and technique. In its broad, etymological sense, hydrology relates to all the waters of the earth. However, as the waters in the atmosphere and in the ocean are also the concern of meteorology and oceanography, the distinctive field of hydrology relates to the waters of the land—the water occurring on the land surface, as snow or ice or as liquid water that is flowing in streams or impounded in lakes and ponds, and the water occurring below the surface, in the soil and underlying rocks. It includes juvenile water, for that water mingles with the water of meteoric origin and obeys the same laws.

Hydrology, thus defined, has two major branches relating, respectively, to surface and subterranean waters, and each of these may in turn be regarded as having two branches. The hydrology of surface water is naturally divisible into that relating to liquid water at the surface (potamology, relating to streams; and limnology, relating to lakes) and that relating to glaciers and other ice and snow (cryology). Although these two kinds of surface water are closely related, the corresponding branches of hydrology are quite distinct in their techniques because the physical properties of water in the frozen state are so different from those of liquid water. Likewise, subterranean water is closely related to surface water, but the corresponding branches of hydrology differ radically in technique because of control by geologic structure and dominance of molecular forces in the subterranean water.

The hydrology of subterranean water has rather appropriately been called geohydrology, using the prefix *geo* in a restricted sense, as in geology. It is divisible into that relating to water in the zone of aeration and that relating to water in the zone of saturation. The water in the zone of aeration is generally called soil moisture and that in the zone of saturation ground water. More exactly, the term soil moisture is limited to water in the root zone, whereas the term vadose water is extensively used to designate water in all of the zone of aeration. Recently, the author has proposed, especially for international use, the terms kremastic water for the water in the zone of aeration, and plerotic water for the water in the zone of saturation. These two branches of geohydrology are closely related but they have been cultivated by somewhat separate groups of scientists and each has a considerable technique that is rather distinctive.

The hydrology of the surface waters is cultivated chiefly by men trained as engineers, but when these men are engaged in scientific study of natural

waters they are hydrologists rather than engineers, whose primary functions are related to construction and utilization. More attention by geologists to the study of surface waters is greatly needed.

The hydrology of soil moisture is studied chiefly by physicists, with associated geologists and engineers. They comprise two groups concerned, respectively, with the agricultural and engineering uses of the soil, and these two groups might well make a greater effort to understand each others' concepts and terms.

In many countries the study of ground water is more or less the concern of a group of geologists and also of a group of engineers. These two groups are likely either to be in competition with each other or to pay little attention to each others' work. This condition also formerly prevailed largely in the different States of this country. The technical force of the Ground Water Division of the U. S. Geological Survey formerly consisted entirely of geologists, but in recent years about one-third of the staff has consisted of men who are graduates in engineering. These engineering graduates are generally better trained in mathematics and physics than are the geologists, and to a large extent they have led the way in ground-water hydraulics. On the other hand, through their association with geologists and their constant contact with geologic problems in the field, they have become geologists in fact—some of them very good geologists—even though they are still engineers by their scholastic degrees and official classification. It is significant that the pioneer in the recent advance in ground-water hydraulics has been Dr. C. V. Theis, who received degrees of both Civil Engineer and Doctor of Philosophy in geology, from the University of Cincinnati. In this connection it should also be stated that the geologists and engineers of the Ground Water Division have the benefit of close collaboration with the chemists of the Quality of Water Division of the Water Resources Branch.

GEOLOGIC CONTROLS IN HYDROLOGY.

It is evident that hydrology is very closely related to geology, for the water which is the subject matter of hydrology is everywhere in contact with rocks and soils, which form the subject matter of geology. From the time the precipitated water reaches the solid earth as rain or snow until it is returned to the atmosphere or the sea, its movements and composition are determined primarily by the geology of the terrane on or in which it occurs.

The relation of geology to ground water is so obvious and well recognized that the subject does not require much elaboration. The rock formations are the natural conduits that take in water from the surface and water expelled from underlying magma, convey it through the earth, and ultimately discharge it to the surface or into the atmosphere or ocean, or yield it to wells. The rock formations are also natural reservoirs that store water in large aggregate quantities and for greatly varying periods, some of it for a very long time. There are infinite variations in the texture, jointing, and crevicing of the different rocks, and these variations make striking differences in the hydrologic properties of the rocks, such as permeability and specific yield, and hence in the hydraulics of ground water, the rate of recharge, and the rate and manner

the ground water is yielded to wells and to springs and streams. The stratification of sedimentary rocks, their dips and folds and their changes in texture from place to place, the unconformities, faults, dikes, and other structural features, all exercise important hydrologic controls. They largely control the occurrence, quantity, head, direction and rate of movement, and location and rate of natural discharge of the ground water; the conditions under which ground-water supplies can be obtained; the magnitude of these supplies and their permanence; the direction and extent to which the effects of withdrawals from wells are transmitted; the interference of such withdrawals with springs and other wells; and the encroachment of salt water.

In the slow movement of ground water from intake to discharge, the water is in very close and long-continued contact with the mineral substances of the rocks, and thus has ample opportunity to take any soluble substances into solution. The chemical composition of the water, and hence its value for the various domestic, industrial, and irrigation uses, depends not only on the original mineral composition of the water-bearing strata, but also on the opportunities for the movement of the water through the strata, and the consequent flushing out of connate water and leaching out of the mineral matter. The opportunities for movement depend on the supply of surface water at the intake, the permeability of the aquifer, the structure of the rock system in creating artesian conditions, the altitude of the intake in providing head, the existence of an open outlet to the surface or into the sea at a depth not great enough to have the discharge blocked by the heavier sea water, and the length of time that these conditions, most of them geologic, have existed. In the course of geologic time the aquifers have become flushed and leached to varying depths, above which they yield water that is fresh enough for ordinary uses or can be rendered acceptable for use by feasible methods of treatment.

All fresh surface waters, of course, depend on the geologic processes that have raised the land above sea level. Surface waters are derived partly from ground waters, but surface waters are in most places less mineralized than ground waters because of their large components of direct runoff and of ground-water runoff from very shallow and well-leached aquifers.

The earth's supplies of fresh water, created through geologic time by natural processes, are surrounded by the great sea of salt water, and in large parts of the land areas they are also underlain by salt water at no great depths. When fresh water is diverted for use, the freshening process is likely to be reversed and salt water may flow up the tidal rivers and canals and inward and upward through the rock formations toward the cones of depression of producing wells, except as the rock structure creates a barrier. Thus the quality of both ground water and surface water is determined largely by a complex of geologic conditions, and the occurrence of fresh water in the earth is essentially the result of geologic processes.

The flow and regimen of surface streams are determined largely by climatic and vegetal controls but geologic controls are equally fundamental and effective. Streams in the Wisconsin drift plains have feeble and sluggish flows because the erosion cycle of these plains is still in extreme youth. Water movement is retarded by numerous lakes, ponds, and swamps, and

much of the water is dissipated by evaporation and transpiration. Streams in a maturely dissected region of hard rocks, such as the Appalachian Mountains, have different controls and different regimen. They tend to discharge their water promptly except as it is held back by forest conditions and the relatively meager reservoir capacity of the surficial rocks. These surficial ground-water reservoirs are actively recharged as a result of the favorable intake facilities afforded by forests, and they discharge their water rapidly, providing a limited but valuable flow in periods of fair weather. This fair-weather flow is accurately forecast by at least one electric power company from weekly measurements of water levels in observation wells. Still different controls and regimen are exhibited by streams draining the sand hills of Nebraska, with their well-sustained ground-water runoff and lack of storm runoff; streams draining the basalt terranes of the Northwest, with their first-magnitude springs that have relatively constant discharge; and streams of limestone terranes, with their subterranean drainage basins that ignore surface divides.

Evidently the geology of surface water, that is, the geology of drainage basins in relation to their runoff, is a subject of great interest and practical importance. It is a subject that has received only a minimum of systematic or intensive study and affords a promising field for further research. Numerous geologic maps and areal reports and a large amount of accurate stream-flow records are already available, but such studies should not be merely office studies of existing data but should include considerable additional field work.

HYDROLOGIC CONTROLS IN GEOLOGY.

As the rocks largely control hydrologic processes, so it is equally true that the water has largely controlled the genesis and history of the rocks and their mineral deposits. Water is probably not essentially involved in the tectonic processes that elevate or submerge the land, tilt and fold the rock formations, and compress, break, and displace them; but it is involved as one of several factors in magmatic and volcanic processes; it is by far the leading agency in the genesis of sedimentary rocks; it is the principal agency of erosion and rock sculpture; it is the agency that has produced all glacial scour and deposition; it has had a complex and important part in the alteration that rocks of all kinds have undergone; it has been a very important agency in the physical and chemical sorting and segregating processes that have for the most part produced both metalliferous and non-metalliferous mineral deposits; and it is importantly involved in the occurrence and recovery of oil and gas. Indeed, the hydrologic controls in geology are so overwhelmingly important that the thesis requires no further elaboration.

In striking contrast to the importance of water in geologic processes is the extent to which hydrology has been neglected in the training of students in geology. Thorough and detailed instruction has been given in mineralogy, petrology, and palaeontology; but hydrology has been touched upon only in casual and random fashion. Courses in hydrology are generally not to be found in the curricula of geology departments, and the older textbooks of geology contain only very elementary and often not very accurate treatment of the subject. One is reminded of the old court opinion which referred to

percolating ground water as "vagrant wandering drops," or another which stated that "the physical laws governing underground water and its subterranean progress are irregular and unknowable with certainty, and such water is changeable and uncontrollable in character subject to secret incomprehensible influences." The ground-water concepts that were formerly taught to students of geology had somewhat of that same flavor. This gap in geologic instruction has been a handicap to professional geologists in their technical work.

In recent years more serious attention has been paid to hydrology in the instruction of geologists, and in general the subject is treated more thoroughly in recent textbooks than it was in the older books. However, much improvement is still needed. It is doubtless true that in the past there has been a lack of source material in English publications, and few English-speaking geologists have had the interest or background to search the literature in other languages. This situation is steadily improving. It will probably not be long until some of the departments of geology in the larger universities will have full-time professors in hydrology, and these will assume their share in the research in the subject and in adapting hydrologic knowledge to the needs of students in geology.

THE SCOPE AND PROSPECTS OF ECONOMIC GEOLOGY.

Economic geologists cover a vastly large and important field. They are concerned with all parts of the earth's crust that are utilized by man. That includes a large part of the solid earth in so far as it is accessible to man, and it includes a very great variety of mineral substances, each with its own distinctive properties by virtue of which it has responded in its own way to the agencies that have produced the earth's crust, and by virtue of which it has its own specific use in our complex industrial system.

If the science of geology is to be developed to the extent of its great potentialities it must be through fulfillment of human needs, that is, through cultivation of economic geology. Economic geology is not merely the application of the science to economic problems, but it creates imperative demands for more intensive geologic research, provides the financial resources for such research, attracts the ablest geologists by its challenging problems, and develops them into keen, wide-awake, and intensely thorough research students. An outstanding example is afforded by the fruitful researches into the character and genesis of ore-bearing rocks by many of those brilliant and scholarly scientists of the past and present who are known as metalliferous geologists. Another outstanding example is the marvelous contribution to geologic knowledge and to the methods of studying stratigraphy and rock structure that have been achieved by that large group of eager and earnest petroleum geologists, who not only have made use of the most refined methods of geologic mapping but have brought into the service of geology new fields of micro-palaeontology, geophysics, and geochemistry.

It has become quite the vogue for geologists to bemoan the lack of public appreciation for geology and the lack of advertising ability on the part of the geologists. I am deeply impressed with the value of geology as a cultural

subject and the great desirability of having it taught in the high schools and presented to the general public by means of effective geologic road guides, etc. However, I have little patience with this inferiority complex. Permanent progress in the science will not be made by more clever radio talks and press bulletins, but by a larger vision among geologists themselves of the potentialities of our science and by the rendering of more substantial service. The prestige which geology has gained during the war has not come by telling the public or the generals how good we are, but by rendering prompt and effective service that only geologists could render in such essential war work as strategic minerals, military geology, water supply, and petroleum resources.

In geology, as in other sciences, it seems difficult to make effective plans for more than a few years in the future. The reason apparently is that scientific research is pioneer work—like that of Stanley in Africa, who could not plan his course wisely because he had no way of knowing what was ahead except to push forward and explore the unknown country. For this very reason, however, we must be currently on the alert, and we may be sure that if we are content to carry on the old procedures in the comfortable old way our science will stagnate and we will be engulfed in the forward march of science as a whole.

Any scientific society that debars the younger scientists from its membership until they reach middle age handicaps itself severely. I believe that any society that represents a particular science or profession should be like a great workshop in which all bona fide workers in that science or profession, both young and old, have the opportunity to be busily and enthusiastically engaged.

THE RELATION OF ECONOMIC GEOLOGY TO ENGINEERING.

For our present purpose the great profession of engineering may be divided into two major classes—that which is concerned with the earth's crust and that which is not. The first class includes mining engineering, petroleum engineering, and that large group collectively called civil engineering. The second class includes the great field of mechanical engineering, with its many subdivisions or associated groups, such as electrical and chemical engineering. The term civil engineering was originally used in contrast to military engineering, but in the broadest sense it is now understood to embrace military engineering. Civil engineering is also commonly understood to embrace nearly the whole field of hydraulic engineering, including water-supply, irrigation, and drainage engineering, and that concerned with sewage disposal, river and harbor improvements, flood and erosion control, and hydro-electric power development. This classification is obviously only approximate, for the groups mentioned in the first class generally involve some engineering of the second class, and vice versa.

Economic geology serves engineering of the first class, that is, engineering related to the earth's crust. However, it is not a subdivision of engineering but a part of the science of geology, with methods and subject matter quite separate from those of engineering.

Economic geology relates to the earth's crust in two different ways, and for our present purpose it can be separated into two subdivisions. The first

subdivision relates to the occurrence, quantity, and quality of the useful mineral and rock products, such as the metals, coal, petroleum, water, clay, building stone, road metal, sand, and gravel. The second subdivision relates to construction on or within the earth's crust, including the construction of foundations for buildings, bridges, and dams, and the construction of railroads, highways, airports, canals, and tunnels, and nearly all the construction that has been mentioned under hydraulic engineering. It also relates to the construction of mines and wells, which involves a very different field of geology than the study of the occurrence, quantity, and quality of mineral and rock products.

The term engineering geology might logically be applied to the second subdivision, that is, the geology involved in the building of structures on or within the earth's crust. For practical purposes, however, the term engineering geology is generally applied to practically all geology that serves civil engineers, including mineral and rock products that are used by them with relatively small amount of processing, such as sand, gravel, road metal, and earth used in dams, and even rocks suitable for manufacture of lime and Portland cement, and water supply. On the other hand, the term is not generally applied to the large amount of important work of the same kind that is done for mining engineers.

THE HYDROLOGY OF EARTH CONSTRUCTION.

Hydrology is involved in economic geology in three important respects. Thus water is an agency in the genesis of most mineral and rock products of economic value; it is a factor in most of the problems of earth construction; and it is itself a uniquely important mineral product. The first of these has already been discussed.

Hydrology is importantly involved in problems of earth construction. Surface water is involved as to quantity and distribution of stream flow, flood stages and discharge, lake levels, and the dynamics of water in rivers, lakes and overland runoff. It is involved in these hydrologic factors as applied to the size and construction of bridges, culverts, dams and spillways, flood-control works and other river and harbor improvements, and all works to control soil erosion.

Water that occurs below the surface is even more generally and intimately involved in problems of earth construction, especially in the problems that are closest to geology. It is involved in problems of leakage from reservoirs, canals, etc., seepage into excavations of all kinds, and the effects of water on the physical properties of earth materials.

The problems of foundations for buildings, bridges, dams, earth fills, and other structures relate largely to the strength of the formations on which they are built, but the acute problems generally arise where the formations are relatively weak and incoherent, and in these the water content and position of the water table are likely to be controlling factors. Likewise, the problems relating to the sub-bases of roads and air fields are largely problems of water content and ground-water levels. The whole subject of frost and perma-frost is also a hydrologic subject.

The construction of dams generally involves questions of leakage under or around the dams, and in some terranes, such as limestone and basalt, leakage from parts of reservoirs remote from the dams.

Drainage of land that is naturally swampy or has been water-logged by irrigation is a ground-water problem, and much more rigorous investigation and control are needed than in past practice if the harmful effects of erosion and excessive lowering of the water table are to be avoided in the future.

Ground-water problems are involved in drainage by pumping from wells and by leading water downward through wells where perched-water conditions exist. They are involved in repressuring oil fields, disposal of oil-field brines through wells, and the protection of potable ground waters in such salt-disposal operations.

Ground-water problems are involved in the laying out of any irrigation project, especially as to leakage of canals and ditches and the loss of water applied to the land, the resulting rise of the water table, the direction of percolation of the added ground water, the damage that it will do, and feasible methods of its disposal and recovery for beneficial purposes. Ground-water problems are involved in the construction of canals for navigation or any other purpose, with respect to seepage losses or, conversely, the drainage of aquifers and lowering of ground-water levels, and both surface-water and ground-water problems are involved in encroachment of salt water that may result from canals that extend below sea level.

Landslides caused by the construction of embankments, canals, and railroad and highway cuts, or that occur in natural terranes, are generally due to a combination of rock structure and water occurrence; and remedial measures largely involve methods of water disposal.

The construction of tunnels and all other projects that require excavation may involve problems similar to those related to foundations and landslides, and they may also involve problems of quantities of ground water that will have to be disposed of initially and perennially, the methods of disposal, and the effects on ground-water levels and water supplies. Mining operations are likely to involve ground-water problems in regard to water entering mines, the lowering of ground-water levels, and methods of removing water from the mines. In many placer mining operations ground-water conditions are essential factors.

Examples could be indefinitely increased to show that practically all operations which relate to the earth's crust also involve, to greater or less extent, the water which is almost universally present, and therefore that hydrology is generally involved in engineering of this type.

WATER AS A MINERAL PRODUCT.

It has often been said that water is our most valuable mineral. Petroleum geologists probably regard this statement as a gross exaggeration and mining geologists may also be skeptical. The statement is true, of course, in the sense that water is the essential mineral for many domestic, power-development, and manufacturing uses, for the production of all foods and other

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vegetable and animal commodities, and for the functioning of the human body. However, water also ranks high in its dollar value on almost any basis of computation. Ground water in this country alone has a surprisingly large aggregate value when consideration is given to the billions of gallons used daily to furnish supplies for about 9,000 public waterworks, supplies used in processing and cooling in a vast number and variety of industrial establishments distributed among most of our cities, water supplies for about six million farms, and water for the irrigation of a few million acres of land, including much of the land having especially valuable crops, such as the citrus fruits. If we include surface water, with which geologists are less concerned, we add enormously to the dollar value—for public water supplies, industrial use, irrigation, power, recreation, fish production, and navigation.

Certainly, water is one of the most interesting minerals for geologic study. Clear, cold, and pure, it seeps imperceptibly from the earth or gushes forth in great volume from rock caverns, forming innumerable springs of exquisite beauty and thousands of refreshing brooks and lakes that contribute much to the joy of human life, besides being of inestimable practical value in sustaining the flows of the larger streams. It is recovered from wells, sunk at the proper places, to yield large supplies for cities, industries, and irrigation, or the sole perennial water supply in an otherwise dry and barren land. It is discharged in large volume from flowing wells that tap artesian aquifers. It is ejected, boiling hot, from thermal springs and geysers, bubbling with various gases or surcharged with dissolved minerals which it deposits on the surfaces. It issues periodically, with uncanny regularity and irregularity, from ebbing and flowing springs, of which 26 are known to exist in this country.

Water is an interesting mineral for geologic study because it occurs and is of economic value in rocks of all kinds—sedimentary, igneous, and metamorphic, ranging in age from pre-Cambrian to Recent; and it is affected by nearly every kind of rock structure—synclines, anticlines, monoclines, unconformities, faults, dikes, etc. In some western valleys ground water is held by faults in subterranean compartment. In southern California the same structural features that give rise to productive oil fields also act as subterranean barriers against sea water. In the Hawaiian Islands igneous dikes form subterranean reservoirs that are of major importance with respect to water supply.

Whereas economic deposits of most minerals are greatly localized, problems of water supply occur in every country and in every State and practically every county in this country. This is because of the universal need for water and because of its bulkiness, which prevents distant transportation, except at great cost. Thus the greatest need for ground-water investigation is often in areas where water is scarce and hard to find.

The per capita use of water has increased greatly in recent years and it will doubtless continue to increase in the future. This is as it should be. The maximum beneficial use of our water resources, with the least practicable deterioration of these resources, is wholly desirable. In the arid West we are approximating more and more closely to a condition of full utilization of all surface and ground waters for irrigation, in so far as they are not needed for other purposes. In the more humid East there have in the past been great

surpluses of both surface and ground water, but this condition is rapidly changing. The streams are being more and more effectively utilized for public water supplies, power, and industrial cooling, and in many municipal areas the demand for ground water for public supplies and industrial uses is approaching or has already exceeded the available perennial supply. With electrification of farm homes and other improvements, the consumption of rural water supplies is increasing rapidly and will continue to increase. It has been demonstrated that supplemental irrigation is profitable for various crops in the East. It is therefore to be expected that irrigation will in the future create greatly increased demands for water and that on many farms consideration will be given to the total supplies of surface and ground water that can be economically recovered. Increased demand for ground water from many sources is reflected in the increased demand for ground-water investigations. Formerly many of the State Geological Surveys gave only scant attention to ground water; now, ground water has become an important part of the work of all of them, except in the States in which the subject is assigned to another agency; and in some State Surveys more attention is now given to ground water than to all other mineral resources.

Water is an interesting mineral for geologic study because it is not like most other minerals, in a static, fossilized condition, but is at present active in the dynamic and chemical processes which through geologic ages have created the earth's crust and produced its mineral deposits. Thus the occurrence of ground water constitutes only the beginning of the subject; a large and more complex part relates to the current movement and work of ground water in response to forces that obey the laws of physics and chemistry. The Geological Survey maintains automatic water-stage recorders on about 350 of its observation wells. The records show that the water levels in the wells constantly fluctuate in response to various agencies, including recharge from precipitation and seepage from streams; discharge by artesian flow, pumping, and transpiration of plants; changes in atmospheric pressure; ocean tides; passing of railroad trains; earthquakes in all parts of the world; earth tides produced by the moon; and various combinations of these agencies. Fluctuations in observation wells in connection with pumping tests are influenced by faults and by the outcropping or pinching out of aquifers, and thus the adequate interpretation of these fluctuations requires consideration of both ground-water hydraulics and geologic structure.

Water is an interesting mineral for geologic study because its development should be planned for perennial use, in contrast to development of other minerals, which inevitably leads to exhausted mines and oil fields. There has, indeed, been much "mining" of ground water, especially during the war—that is, development of water supplies by depleting the storage in the aquifers. The major objective of ground-water investigations is, however, much more constructive, namely, to bring about maximum and optimum development of water supplies that will be perennially secure—an objective that is ultimately attainable to a great extent by wise use of the large storage capacities of aquifers. It is a truly vast undertaking that will require the application of specialized knowledge and technique, much of which is yet to be developed.

It is an exceedingly important and fascinating undertaking that should contribute much to permanent human welfare.

A survey of the whole subject appears to lead to the conclusion that geology relating to the water of the earth will in the future have an important place in geologic research and teaching, and that there will be a fairly large and increasing demand for geologists in this field, not only in the Federal and State geological surveys but also in the geology faculties of universities and technologic schools and in the consulting field, and not only in the United States but in other countries as well.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

THE CONTROL OF IMPOUNDING STRUCTURES ON ORE DEPOSITION.

ROBERT A. MACKAY.

ABSTRACT.

Various structures have been described from time to time as superimposed strata, blankets, traps, dams, inverted ponds and ponds. It is the theme of this paper that the relatively impermeable barriers that are common to these structures impounded the solutions in such a manner as to cause the metals to be deposited within the structure and to allow the solvent or ore carrying fluid to pass on *through* the relatively impermeable barrier.

It is shown that some elements require a more perfect barrier than others to impede their progress and these differences are reconciled with the general position of the metals in the hydrothermal series. The phenomenon responsible for this impedance is held to be exosmosis if the metal is in true solution and dialysis or ultrafiltration if the metal is in colloidal form. It is argued from the work of Freundlich and others that there is in fact a difference only in degree and not in kind between these phenomena.

The physical chemistry of the process is first dealt with, after which examples of impounding structures in the field and in the literature are described, commencing with the present author's original paper on impounding some years ago. Finally the possible applicability of the theory to regional replacement is discussed.

INTRODUCTION.

WHEN either a true or a colloidal solution within a sufficiently finely porous vessel is subjected to adequate pressure, water passes through the walls of the vessel leaving the salt within.

This paper introduces the proposition that when ore-bearing solutions have encountered suitable impermeable (or more accurately semi-permeable) barriers, the solutions have been so impeded that the water has passed on while the mineral has been impounded and deposited.

Two uncommon words have been used, another has been coined, and of another the writer has seen very loose usage in recent publications. It is, therefore, advisable to define them and also some other words used in this paper. In a sense some of these definitions serve to summarize the physical chemistry section.

Exosmosis. (Resuscitating a word used in the last century.) Osmosis is reversible but the passage of water into a solution is the direction generally thought of. The less common use of the word is for the reverse of the process, here called exosmosis.

Ultrafiltration. (Freundlich.) The separation of particles below normal filterable size from the liquid in which they are suspended. Normal filters have pores up to 1 micron.

Hypofiltration. This word is coined to include ultrafiltration, dialysis and exosmosis. There is no one word which embraces them all in spite of the fact they differ only in degree. Hypofiltration is suggested to include such processes below the sizes of truly filterable products.

Impedance. If a solution, true or colloidal, is travelling and meets a semipermeable barrier it is impeded. It is not stopped. The plain English verb needs no comment but the use of the derivative noun is unusual except in electrical science.

Lyotropic Series. A series put forward by Freundlich which places elements in an order determined by the change of internal pressure caused by them in liquid.

Hydrophilic. The affinity for water displayed by a molecule or ion. This is one of the lytropic properties.

Incompetent Rock is one which gives way to pressure by flexing as a whole. *Competent Rock* is one which reacts to pressure by fracturing. These two terms are used comparatively with one another.

PHYSICAL CHEMISTRY.

To justify a radical theme the basis must be thoroughly investigated. Therefore this section of the paper, of necessity somewhat involved and theoretical, is placed before the general thesis. Nevertheless, a reader who is allergic to physical chemistry may pass this by, missing nothing essential to an understanding of the paper, the process, or its applications; though it is necessary for demonstrating its scientific tenability.

In stating that any solution subjected to pressure within a finely porous vessel will lose its water, a true generalization has been attained at the expense of rather loose usage in the expression "sufficiently finely porous." For a complete understanding a rather full discussion of osmosis, dialysis, and ultrafiltration is necessary. It will be convenient to take the most complex first.

Osmosis.—The action of this phenomenon is best understood by the description of two of the methods used to measure osmotic pressure.

Lord Berkeley's Method.[1] The solution of which the osmotic pressure is to be measured is placed in a container, within which is a porous cylinder in whose walls have been deposited copper ferrocyanide gel. The inner cylinder is filled with water and connected to an external capillary, which shows whether there is addition to or subtraction from the volume.

Arrangements are made for subjecting the outer jacket to pressure. At low pressure the water will pass from the internal cylinder to the solution in

[1] Findlay, A.: Osmotic Pressure. Longmans Green, 1919, p. 32.

the jacket. As the pressure is raised on the jacket the water flows more slowly through the semi-permeable walls of the cylinder until, at a certain pressure, it ceases. This is the osmotic pressure, and if the pressure is raised further the water passes back from the solution to the pure water in the cylinder. The water in the capillary is then seen to rise.

de Vries Method.[2] The living cell of a plant is placed in a solution under the microscope. If the cell shrinks the osmotic pressure of the solution is greater than of the cell contents, because water is passing out of the cell to the solution. If the cell swells it has a greater osmotic pressure than the solution as the water is now passing from the solution to the cell.

In the former case a point can be reached, by diluting the solution, where the solution is isosmotic with the cell and no transfer takes place, since one of the factors controlling osmotic pressure is concentration. From a known solution at known concentration, the standard of the cell can be determined. From this in turn the osmotic pressure of other solutions can be found.

This is not an accurate method but it well illustrates the nature of osmosis. It is applicable to substances which do not attack the delicate membranes of the cell. Such substances may however attack the colloids generally employed to fill the pores of pots.

In both these cases, when the water passes away from the solution, resulting in greater concentration, exosmosis [3] is the process involved.

This paper is not greatly concerned with the actual magnitude of the osmotic pressure because that figure is not directly related to the ability of the salt to pass through a given membrane, a characteristic that depends on other properties and is dealt with under penetrability. Nevertheless a consideration of it is desirable to show that the pressure necessary to pass the water away from a solute is a reasonable one.

The osmotic pressure of a dilute solution of a non-electrolyte follows the Van't Hoff gas law:

$$PV = RT$$

or may be stated as

$$P = \frac{CT}{M} \times K = 0.082 \frac{CT}{m},$$

where P = Osmotic pressure; atmospheres; C = Concentration; gram/litre; T = Tem. (absolute); M = Mol.-Wt.; K = Constant.

Using this formula the approximate osmotic pressures, at 100° C. and saturation, of some of the more soluble salts that might occur in ore solutions would be as follows, if the law there applied.

[2] Jones, H. C.: The Nature of Solutions. Van Nostrand Publications, 1917, p. 69.

[3] Dutrochet: Reference indirect. "Exosmosis" is a term which was used formerly in this sense. It is revived as applicable to this paper.

TABLE 1A.

OSMOTIC PRESSURE OF SOME ELECTROLYTES.

Ag_2SO_4	0.2 atmospheres
$HgSO_4$	0.01 atmospheres
Na_2S	50.0 atmospheres
$CuSO_4$	36.0 atmospheres
$ZnCO_3$	0.01 atmospheres
$ZnSO_4$	110.0 atmospheres
$PbCl_2$	1.65 atmospheres
$ZnCl_2$	300.0 atmospheres
$CuCl_2$	88.0 atmospheres

For unsaturated solutions or less soluble minerals the figures would be far less.

But these substances being electrolytes the gas law is departed from by a degree varying with the concentration or rather degree of ionization. This is due to ionization, probably the hydration of ions. An example is lithium chloride which gives the following results for osmotic pressure:[4]

TABLE 1B.

OSMOTIC PRESSURE OF LITHIUM CHLORIDE.

Concentration (Normality) at 30° C.	0.1	0.3	0.6
Observed Pressure (B^1)	4.317	13.768	29.535
Calculated Pressure (P^2)	2.472	7.415	14.830
Ratio ("i") = P^1/P^2	1.746	1.857	1.992

From the work of de Vries on Isotonic substances[5] it would seem that salts of the divalent cations have a larger ratio of departure, in the order of 2.5–3 on the same concentration range. This figure "i" is therefore influenced, and approaches in value the total number of ions formed on dissociation. Thus "i" would be expected to be between 3.5 and 4 for the salts of the trivalent metals. By reference to various published data for the value of "i" at various concentrations it would be possible to recast Table 1 with actual results, but for the purposes of this paper only the order of such results is of importance.

The general order of the osmotic pressures in Table 1A is well within the geological range of possible pressures except perhaps in the case of the very soluble zinc chloride, where a really large pressure would be involved. The writer, however, believes this salt can be safely taken as unlikely to be concerned in primary solutions. Graton's paper seems to support this. But in dealing with the effect of the nature of solutions it will be seen that there is also an alternative explanation regarding the method of carriage of zinc.

Ultrafiltration.[6]—Ordinary filtration will not remove finer colloidal particles from a colloidal solution. If however a film of collodion or parchment

[4] Jones, op. cit.
[5] Jones, op. cit., p. 74.
[6] Freundlich, H.: Colloid and Capillary Chemistry. Hatfield Translation, Methuen, 1926, 372.

separates the solution from water, a very small to moderate pressure will drive the water through the membranous barrier, concentrating the colloidal solution. By higher pressure nearly all, and in most cases all, of the water can be removed except with very lyophylic sols, which however do not include any of the salts of the metals discussed in this paper. The relation of ultrafiltration to osmosis is one of degree as is demonstrated by the fact that colloids do have a low osmotic pressure.[7] Freundlich [8] also cites "semi-colloids" as solutions forming an "unmistakable transition to true solutions." Their properties are in every way intermediate. The Ostwald classification (Table 2) also emphasizes this transition.

Dialysis.—This is a special case of ultrafiltration, where the colloid is dispersed in a solution of an electrolyte and where there is solution continuity on both sides of the membrane. The electrolyte can pass if the barrier is suitably chosen for the degree of semi-permeability: the colloid cannot. Very low pressures, such as the weight of the liquid itself, are needed in the case of lyophobic sols. Because of the difference between exosmosis, dialysis and ultrafiltration being of degree only as far as the separation of the disperse from the continuous phase is concerned, the author introduces the word hypofiltration to cover the whole range below true filtration.

Nature of Barriers.—Neither for osmosis nor dialysis is there a universal barrier, or semi-permeable membrane; a given membrane is semi-permeable only in a specific sense to a stated solute. A "membrane" or barrier which may be impermeable to one salt, may be quite permeable to another. In this paper, the word semi-permeable membrane is used as little as possible, though its use is classic in this connection. First, modern semi-permeable membranes never are in a true sense membranes, and secondly, the application of the word membrane in geology is incongruous, and likely to present a wrong picture of the effect it is sought to describe. For half a century the semi-permeable membranes of the laboratory have been, in the main, porous pots, in the pores of which gels have been deposited. To obtain perfect retention of a solute, most intricate procedure has been necessary.[10] But this is probably because the use of a pot of great thickness involves time out of keeping with laboratory procedure both for preparation and use and might cause the capillary resistance to exceed the osmotic pressure and thus make measurement by standard methods impossible.

The factors which determine whether a barrier will or will not be permeable to a substance are:

(*a*) Effective size of pores (*i.e.*[11] actual size as modified by absorption effects).

(*b*) Properties of the substance (*i.e.* molecular size,[12] degree of ionization, the rate of penetration which is a factor of hydrophilic strength,[13] and valency by virtue of its effect on hydrophilic strength.

[7] Freundlich: Idem, p. 376.
[8] Freundlich: Idem, p. 532.
[10] Morse: Am. Chem. Jour., 1911, vol. 45, p. 91.
[11] Freundlich: op. cit., p. 744.
[12] Findlay: op. cit., p. 24.
[13] Freundlich: op. cit., p. 747.

It is not affected by the magnitude of the osmotic pressure.

As far as the writer can determine, though the effect of each of these factors is quite well known, knowledge of them can not yet reach a point where the subject is capable of mathematical treatment. This is not difficult to understand when the factors are considered individually. The average effective size of pores is easy to determine in the case of a simple porous vessel, but uniformity is rarely possible so that there is an effect due to maximum pore size, which is less easy to determine. When colloid gel is deposited within the pores, the subject assumes even greater complexity because adsorption phenomena reduce the effective size (Fig. 1) of the pores.

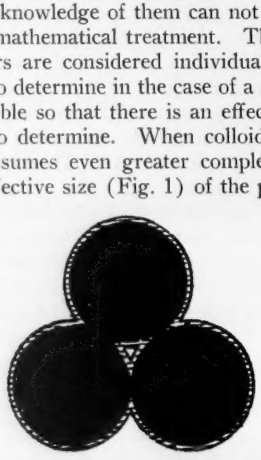

FIG. 1. Effective pore space showing reduction of actual pores by absorption layer (shaded) around particles (black). From Freundlich.

It is known that osmotic effects take place up to a maximum pore size of half a micron, and are independent of the nature of the barrier material, except in so far as this controls the *effective* pore size. Thus approximate pore sizes, to accomplish given impedances, vary from a micron at the lower limit of filtration to probably about 3 millimicrons for the most difficult molecules for osmosis.

It may be urged that another theory of osmosis [14] stipulates that this pore or capillary size is not the controlling factor in osmosis, but that hydration and dehydration of the membrane is. Such a theory presumably regards the pores as mere support for the gel of the barrier; that is to say, the pores of the pot, being too large to impede the molecules or ions, as the case may be, are reduced in size by a suitable deposition of gel within them. It has been shown that further reduction is achieved by subsequently depositing precipitate of an electrolyte within the gel. The writer thinks that the balance of opinion shows that capillary size is the more important factor, but it will later be shown that this conception would fit with the major thesis. The two theories are by no means irreconcilable, for Freundlich is quite clear that the process must not be regarded as plain sieve action, but is conditioned by adsorption in which hydration plays a part.

The greater the molecular size the less the penetrability through a given membrane.[15] This was the first relation to be determined, being of an obvious nature, but it would only seem to apply to compounds of related nature such as sugars or some salts with a common ion.

[14] Jones: op. cit., p. 230.
[15] Morse: 1906, 31, 33 and Phil. Trans., 1906, vol. 206, p. 486.

A far more dominating control appears to be the degree to which the salts are hydrophilic or hydrophobic, *i.e.* ionic affinity for water. This forms an easy comparison for the cations, within a given valency group of the periodic table, but ceases to be so from group to group. It is a complex subject, to be much more fully developed in the next section.

Summarizing: whether a specific dissolved substance or dispersed solid can be separated from the ambient liquid by impedance is mainly a matter of pore size, and this constitutes semi-permeability. The pore size necessary for the retention of a given substance by hypofiltration is related to the particle size, and in the case of exosmosis this is a matter of molecular size and (hydrated) ionic volume instead of discrete particle size. The actual pore size is reduced to an effective pore size by adsorption effects, and the divergence between the two increases in the lower size ranges.

This may be clearer from the following table. Wolfgang Ostwald's classification is in the first column. In the other columns the source is given where it is from authority.

TABLE 2.

FILTRATION AND HYPOFILTRATION.

Wolfgang Ostwald's Classification	More Common Usage	Size[16] Limits of Particle Millimicrons	Method of Impeding, and Stopping the Disperse Component		Barriers (and Membranes)	Order of Pore Size (Actual) Millimicrons
Coarse Dispersions	Precipitates	+1,000	Filtration		Filter-paper untreated	+1,000[19]
	Suspensions. Emulsions	−1,000 + 100			Fine filters. Treated filter-papers	−1,000 + 300
Colloidal Dispersions	Suspensoids. Emulsoids (colloidal solutions)	− 100 + 1	Hypofiltration	Ultrafiltration Dialysis	Fine unglazed porcelain. Parchment.[5] Colloidion	± 500 ± 50?
Molecular Dispersoids	True solutions	− 1 ± 0.5	Hypofiltration	Exosmosis	Unglazed porcelain, very fine.[17] Compressed metal powders. Metal films	− 500[17]
Ionic Dispersoids	True solutions (ionized)	− 0.5	Hypofiltration	Exosmosis	Animal membranes. Layer of clay. Gel-filled pots. Ditto clogged with precipitate[17]	10–20[20] 5?

Note: Large molecules have a diameter of 4 and average unit crystals of 0.5 millimicrons.[21]

[16] Zsigmondy: "Kappilarchemie," 1920, p. 29 from Freundlich, op. cit., p. 398.
[17] Findlay: op. cit., p. 96. Quoting Bigelow, Jour. Am. Chem. Soc., 1907–29, p. 1675.
[18] Freundlich: op. cit., p. 268.
[19] Freundlich: op. cit., p. 378.
[20] Freundlich: op. cit., p. 745.
[21] Gaudin, E.: Princ. of Min. Dressing, 1939, p. 54. (Inserted to emphasize overlapping nature of classification.)

The size limits given for particle size are naturally not precise but give the order of size of the particles of the different ranges and the order of actual size of pores to effect a separation in this range. Precision is impossible in such a table because some molecules are larger than some colloid particles, and just as there can be no sharp division between filtration and ultrafiltration, so there is in all likelihood no real gap between osmosis and dialysis. The semi-colloid range would need more investigation than it has received to prove this conclusively.

Penetrability of Substances Through Semi-permeable Barriers.—The former paragraphs have been on the safe ground of fully demonstrated scientific fact. Now one must pass somewhat into an inductive field where, though the influence of the concerned factors has been clearly demonstrated, the degree of influence of each has not, and in particular, experimental data on the lyotropic characteristics of the common hydrothermal metals are scanty.

For simplicity exosmosis has been discussed as though it were uni-directional, and the resulting effect can fairly be so regarded where the membrane is perfect. To be more precise the osmotic pressure is due to a difference of relative velocity of solvent and solute through the membrane. It is clear, however, that where the membrane is truly semi-permeable, that is to say, impermeable to the solute, the velocity of the latter becomes nil and the process can in this case be regarded as unidirectional. But it is well to bear in mind this dynamic aspect of osmosis for it makes it clear that even when a barrier is not perfect the effect will be the same though in less degree. Thus a bed of porous material, restricting but not totally impeding anion, radicle or molecule, will cause a concentration gradient roughly parallel to the hydraulic gradient.

It has been shown that the molecular size (probably as the function of ionic volumes as distinct from the influence that ionic volume has on hydration) is one factor determining whether a substance will pass a given semi-permeable divide. But there is another, initially paradoxical, but far more important factor. The penetrability of an ion depends on its lack of affinity for water,[22] and within a valency group of the periodic table this is inverse to, in fact in direct contradiction of, the ionic size.[23] Thus the penetrability of salts of the alkali metals is:[24] Li Na K Rb Cs. This statement goes a little farther than the authority quoted, for as stated above at a certain point of pore size velocity becomes zero. This water-affinity is not to be confused with solubility. Solubilities do frequently run more or less parallel with it, but there are radical departures. Rather is it an inverse function of Freundlich's lyotropic series of which he says:[25]

> We can therefore distinguish from the group of properties which are comprehended in the Van't Hoff theory a second independent group, which are due to the change of the internal pressure by the solute. These properties will be described as lyotropic; the influence of the solute upon the surface tension, the compressibility, the solubility of difficultly soluble substances, and others will be

[22] Freundlich: op. cit., p. 747.
[23] Jones: op. cit., p. 322.
[24] Freundlich: op. cit., p. 747.
[25] Freundlich: op. cit., p. 49.

called lyotropic influences. Unfortunately satisfactory methods of determining quantitatively this effect of the solute upon the internal pressure are still wanting. Hence the theory of lyotropic properties is at present, in contrast to the Van't Hoff theory, quite in its infancy.

More simply, Armstrong [29] earlier drew attention to the relation of penetrability and the hydrophilic properties when he said:

> The compounds which penetrate the (particular) membrane . . . are all substances which attract water presumably only to a minor extent and which exist to some extent in solution in an unhydrated condition; those which cannot penetrate it on the other hand probably all form hydrates of considerable stability in solution.

The parenthesis in the quotation is added as justified by the context.

A more recent quotation may further clarify the conception. It deals with the rate of travel of ions in electrolysis but is based on the same fundamental of ionic hydration. In discussing electrolysis Thorpe says [26a]

> This shows the remarkable fact that the cation transport numbers (*i.e.* rate of travel of cations) of the alkali chlorides increase with the atomic weight, whereas it would be expected that the mobility of the unhydrated ions would decrease with the atomic weight. Bredig in 1894 suggested that the metal ions carried with them water which increased their size and thus slowed them down and this view is in accordance with the above results.

The values of the hydration of ions obtained by different methods have shown poor agreement and there is still no unanimity of opinion as to the exact relationship of ions and solvent molecules. But as between different investigators there is no lack of agreement as to the orders of hydrophilic affinity of the ions investigated.[26b] Freundlich does not give the lyotropic series for all the elements together apart from: Li Na K Rb Cs, he gives [26] by inference from adsorbability: K, Na Mg Ca Al which may be slightly modified according to data from Rice [27] and becomes Na K Mg Ca Al.

Elsewhere [28] he gives the following figures for the number of water molecules attached to the alkali cations:

Li 120; Na 66; K 17; Rb 14; Cs 13

which is inserted as an example of the hydrophilic aspect of the lyotropic series within this group.

Freundlich does not give the relative positions of any of the heavy metals. The nearest he comes to this is a series quoted for adsorption which is roughly inverse to the lyotropic (hydrophilic) series (and therefore in the same sense as the penetrability series). It is:

Ag Hg Cu Pb Zn.

[29] Armstrong, H. E.: Proc. Roy. Soc., 1909, vol. B. 81, p. 94.
[26a] Thorpe's Dictionary of Applied Chemistry, Longmans, 1943, p. 237.
[26b] Thorpe: op. cit., p. 296.
[26] Freundlich: op. cit., pp. 202–203.
[27] Rice: Electronic Structure and Chemical Binding, p. 220.
[28] Freundlich: op. cit., p. 59.

It will be noted that, as before, this is not a solubility series. Freundlich quotes it as in general proportional to the solution pressure which is a function of the lyotropic series. The position of copper in this series is an anomaly as far as relation to ionic volume is concerned. There is however evidence to show that comparisons between different periodic groups are difficult, and it has been shown elsewhere that there is some indication that copper may be more hydrophilic than zinc. This is where Jones [30] has shown in a series of Carnegie Institute Publications that the temperature coefficients of conductivity of solutions vary with the degree of ionic hydration. He gives figures where this coefficient is definitely higher for copper than zinc, so that on penetrability copper should be below zinc.

It is understandable that this hydrophilic property should reduce penetrability, for the complex molecules and complex ions due to hydration would naturally be larger than the unhydrated ions and secondly the very water affinity would militate to some extent against the eventual parting. On the other hand some weight must be given to the earlier discovery of molecular size which was found to be the controlling factor for the non-electrolyte solutes and which one imagines must have an influence at the moment of parting.

Applying these principles to the common hydrothermal metals the order of penetrability can be first considered on the hydrophilic series. This can be taken as proportional to the ionic volumes, which gives the order:

Hg Pb Cu Sn Zn.

The placing of the Sn beyond the Cu of equal ionic volume is fairly decided on the fact, agreed fully by Jones and Freundlich and Rice, that higher valency makes for greater water affinity. In fact the charge on the tin ion is so much greater than in the case of the other metals that there is little room for doubt that it is the most hydrophilic.

The author submits that there is full reason in moving zinc above tin on molecular size and valency grounds. It may be objected that if so the molecular weights of Hg and Pb should influence their position. In reply it is urged that the author believes they do so, for in the hydrophilic series is a large magnitude gap between them and the next metals, but a small penetrability difference would fit the facts as regards the close association of lead and zinc in nature.

This still leaves zinc as the one anomaly, but if the argument as to temperature coefficients be admissible, and of this the molecular physicist must judge, then the order would become:

Hg Pb Zn Cu Sn.

And this is the actual order of penetrability observed in nature. These alterations are diagrammatically represented as under:

[30] Jones, H. C.: Carnegie Inst. Publ. 198, 1941, p. 217.

TABLE 3.

PENETRABILITY (DIAGRAMMATIC).

Metal (Ionic Volume Order = Provisional Hydrophilic Series)	Ionic Radius	Sense of Adjustment for Ionic Size (as Affecting Molecular Size)	Sense of Adjustment for Valency Affects Hydrophilic Series	Sense of Adjustment for Temp. Coeffic. (see above)	Suggested Resultant Penetrability
Hg	1.25	↓			
					Hg
Pb	1.06	↓			
					Pb
					Zn
Cu	0.96			↓	
Sn	0.96		↓		
					Cu
Zn	0.88	↑		↑	
					Sn
Notes		With respect to copper in each case	Tin only on account of its 4-valency	Copper and zinc. Others not anomalous	

Reverting to the opening sentence of this paragraph the author admits that there are one or two unproved links in this reasoning. But as far as his available literature shows this is all the data there are at hand upon which to reason. In considering the scantiness of data it is interesting that, as Rice shows for the alkalis and alkali earths, experimental results for ions in solution, though following each other in the same *sense* as the lyotropic series, bear no resemblance *whatever* to the numerical values obtained from theoretical calculations of ionic radius, in fact negative values are obtained (which

he interprets as due to hydration forming complex ions). Moreover, the writer asks forbearance until the section on older theories is dealt with; for this penetrability series, even unadjusted, is much nearer the observed facts in nature than are theories which ask us to believe that in ordinary fissures the least soluble minerals deposited last and the most soluble first. It is certain that the nature of the chemical bonds, whether polar or co-valent, would be a further influence on penetrability, and probable that the greater the departure from co-valent bonding, the less the penetrability. But this is beyond the scope of the present paper and is mentioned to show that there are other factors which would have to be taken into account before the few anomalies to the theory can be explained.

IMPOUNDING STRUCTURES AND THEIR INFLUENCE.

General Statement.—The influence of so-called impermeable barriers on the formation of certain orebodies has by no means been overlooked in the literature, and numerous widespread instances will be quoted in their proper place. So far as the writer knows, however, there has been no attempt to correlate such deposits or to explain the general reason for them and there has been no attempt to apply the explanation to the effect of less obvious barriers. One of the broadest general statements the writer knows is Lindgren's argument that fault gouges on orebody walls are of the same nature as overlying barriers.

The thesis of this paper is that a very large class of deposition is controlled by geological barriers, both obvious and latent, having impeded the progress of ore-bearing solutions, and that the nature of such barriers has been to allow the water and some radicles to pass on, while other radicles have been impounded. It is contended that the barriers were not impermeable but semipermeable, and evidence will later be adduced to show that this is so. It has already been shown that metallic compounds can be separated from the water which carries them by hypofiltration, and it has also been shown that semipermeable barriers can exert differential effects as between the particles, molecules or ions of different substances.

The Nature and Function of Geological Barriers.—Impounding structures assume various forms. The essential is that the passage of solution within a competent rock shall be restricted by an enclosing or partially enclosing incompetent rock. The expressions competent and incompetent are throughout used comparatively to one another. It will be noted for instance in ensuing examples that andesite has been called competent with respect to marl and incompetent with respect to rhyolite.

Such structures have been variously described as superimposed strata,[32] blankets, impermeable barriers,[33] traps,[34] ponds [35] and impounding structures.[36]

[32] Mackay, R. A.: The influence of superimposed strata on the formation of certain lead zinc ores. T. I. M. M., 1925.

[33] Lindgren, W.: Mineral Deposits, 1933, p. 200.

[34] Schuette, C. N.: The occurrence of quicksilver bodies. T. A. I. M. E., pp. 40, 3–88. Wisser, E.: Geologic parallels. ECON. GEOL., May, 1939.

[35] Schnellman, G. A.: Applied geology at Halkyn Dist. Mines. T. I. M. M., 1939, p. 685.

[36] Mackay, R. A.: Contrib. remarks to preceding paper, 1940, p. 639.

A list of structures fulfilling the requirements, while not exhaustive, clarifies the picture.

Domes	*e.g.* Shale over limestone or sandstone.
Anticlines	*e.g.* Shale over limestone or sandstone.
Blankets	*e.g.* Shale over limestone.
Monocline and steep strike fault	*e.g.* Shale over sandstone, normally faulted.
Lens in fissure	*e.g.* Quartz in Schist (applies where mineralization is known to be later than first fracturing).
Overthrusts	*e.g.* Gouge over any rock.
Intersecting inclined faults	*e.g.* Gouge enclosing any less competent rock.
Inclined faults	*e.g.* Gouge over quartz.
Anticlinal rolls	*e.g.* Andesite over rhyolite breccia.

The first reaction of any geologist to such a list may well be that such structures merely exerted a guiding effect on the solutions. The writer would agree that this might be so except for the following facts, corroboration for which will be quoted in the succeeding section:

1. Evidence can often be seen that the direction of travel of the fluid was through the barrier, by mineral change or small deposition along minor fissures.
2. Maximum deposition is frequently in places which would be zones of maximum stagnation as far as solutions were concerned if the barriers were truly impermeable. The quantity of fluid would therefore be inadequate to deposit much ore from moderately concentrated, much less from dilute solutions. It would in fact be a small fraction of the pore space. Replacement would not alter this for once it had taken place no new fluid could come in unless the solution were in motion.
3. Instances will be quoted where the very fact of unrestricted passage has resulted in no ore deposition in positions where there is every reason to suppose that metal bearing solutions must have passed.

To illustrate the first two points, one cannot do better than refer to Lindgren's [37] diagram and quote two sentences which he uses in connection with it. First he says,

> the occurrence of ore in horizontal extension *below* such barriers is in fact one of the best indications we have, that the solutions have been *ascending*

(the second italic is the present writer's). The diagram strongly suggests that he considered that some solution ascended through the blanket, and later in a similar connection, he says,

> when one fissure is faulted by another deposition may occur because the circulation becomes impeded at the fault and partial stagnation follows.

[37] Lindgren: op. cit., p. 200, Diagram 85.

It is inconceivable, however, that a point of *stagnation* or even "partial stagnation" should be the locus of an orebody, for surely more ore is to be expected where most solution has circulated, and certainly not where the least has passed. Indeed in common with most geologists, the writer believes that it *is* in channels of solution travel that ore is deposited, and he merely introduces the conception that the barrier has stopped the progress of the *ore radicles* and not the fluid as a whole. Thus the apparent zones of stagnation are in reality the lines of travel of the carrier fluid.

This principle of impedance is easy to accept for the earlier classes listed on the last page, but it may still be urged that the succeeding types are merely ordinary channels. Here the author must be less direct, relying on analogy with the definite classes and the fact that acceptance of the theory explains a number of hitherto inexplicable things, notably the significance of the well-known so-called temperature series (Hg, Pb, Zu, Cu, Sn), which is considered in a separate section.

It is considered that the step from one of these structures to the next is a matter of degree and not kind, and that reconstruction of an existing geology over an orebody often results in such structures as an anticline, or a termination of a monocline by a close textured fault zone, both of which are impounding structures.

The pressure necessary to pass water away from a solution through a water saturated barrier can be quite small as is shown in the examples of osmotic pressures. The back pressure of a barrier to water could well be less than that opposed by a more open but longer track through the normal fissures of the enclosed competent host channel.

The Effect of the Nature of Solutions.—The nature of the ore solutions must in some degree affect the tenability of this theory of deposition. The theory is consistent with a wide variation in the nature of solution, either electrolyte or colloid, for hypofiltration applies to both. In discussing the inadequacy of some of the older theories of deposition the inadequacy of gas transfer is dealt with, and it will not be considered here.

Graton [38] has summarized the work of the authorities and from his paper it is admissible to accept that the sulphides were transported in alkaline solution. He submits the possibility that the solutions may have become acid at comparatively shallow depth. Since the work of Schuette and Dreyer strongly indicated alkalinity as high up as mercury, perhaps decreasing alkalinity would be preferable or equally tenable. Graton expresses agreement on the belief that the solutions were relatively dilute.

Graton believes, as do others, that colloidal deposition is not an important factor. Lindgren,[39] Rastal [40] and others on the other hand believe it to have been effective. Boydell's [41] major paper, while possibly overstating his thesis, is not by any means negligible and the present writer considers that there is overwhelming evidence of colloids in many epithermal deposits. He submits

[38] Graton, L. C.: The nature of the oreforming fluid. ECON. GEOL., 1940.
[39] Lindgren: op. cit., pp. 124, 125.
[40] Rastal, R. H.: Physico-Chemical Geology, p. 241.
[41] Boydell, H. C.: The role of colloidal solutions in the formation of ore deposits. T. I. M. M., 1924.

the possibility that in hypothermal and most mesothermal depositions there were no suspensoids, or only negligible very fine (unimpeded) suspensoids. The decreasing alkalinity may well have led to the formation of suspensoids and it is probable that they would be at first of very small particles due to very slowly changing conditions, which conditions, however, would be changing in an environment that was not favorable to the existence of the metastable state.

The relevancy to the thesis of the foregoing observations is this: the only type of solution which might be dammed rather than impeded by a semi-permeable barrier is an electrolyte of high concentration, such as $ZnCl_2$ or possibly $ZnSO_4$, which would have an osmotic pressure that would be likely to be above that of the motive force. The discussion above suggests that it is unlikely that salts of this nature were present in important amount in alkali solution, particularly as the solutions conceived were not in a high state of oxidation. But if salts of such nature were present it is still conceivable they were in the colloidal state before they reached the trap that impeded them, as it is in the epithermal zone in which there is most evidence of colloids.

The immense volume of water necessary to transport metals has often been put forward as an objection to many postulated solutions. However by way of quantitative illustration (not actually suggesting that deposition there took place) a simple calculation shows that the volume of water disgorged at the Ten Thousand Smokes of Alaska could deposit 450 tons a day of cinnabar, which, unaided, is the most insoluble of the sulphides. The figures on which this is based are Bowen [42] for the quantity of water, and Dreyer [43] for mercury sulphide solubility in alkaline solution. Who knows that there is not a trap even now below such outlets?

The Passage Through Geological Barriers.—The undemonstrable part of the thesis is that water by itself, or carrying certain solutes, electrolyte or otherwise, did pass these rock barriers, that is, that clays, shales or lava bodies can be semi-permeable. Undemonstrable in the laboratory and perhaps difficult of conception though it is, the author contends that it can be seen to have actually taken place for these reasons:

(1) Mineral is often found within the barrier, sometimes through its entire thickness, though it is rarely economic in amount. It is fantastic to conceive that either sufficient solution penetrated the barrier and stagnantly deposited the amounts of mineral found in it; or that it moved out, *i.e.* circulated up into and then down out of the barrier.

(2) Other orebodies or uneconomic mineralizations are found beneath higher barriers even where the barriers are fairly perfect. They are usually not so large except where the first barrier was poor. Examples will be quoted in their proper place.

[42] Bowen, N. L.: The Evolution of the Igneous Rocks. Princeton Univ. Press, 1925.

[43] Dreyer: The geochemistry of quicksilver mineralization. ECON. GEOL., vol. XXV, p. 17. (This author also refers to the trapping "hypothesis applying to a certain extent to any hydrothermal body.")

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(3) If the fluid did not pass the shale then the position of the impounded ore deposit becomes a locus of stagnation, not a place where great deposition would be expected, for no solution can deposit more of its solute merely because it stays longer in a given place.

In a former paper which dealt briefly with the subject as regards lead it was urged in discussion that a body of shale could not pass water unless solution contact were established on both sides. It seems to the writer that given temperature, pressure and time in moderation nothing is more probable. Shale is full of colloid particles which will absorb water, and, under pressure, this would pass from particle to particle. This is what the author referred to in stating earlier that the theory was not irreconcilable with an alternate theory of osmosis, which postulated successive hydration and dehydration in the "membrane." He considers, however, that the intermicellar *pores* ("effective" intercolloid particle pores) would here also constitute the actual impeding barrier.

That the openings in rocks are of sufficient and of suitable size to effect passage on the one hand and hypofiltration on the other is not in serious doubt. The passage through the host rock need not be considered for it can be assumed that supercapillary openings, that is, openings above 250 microns, exist in competent rock to considerable depth. In the case of the incompetent rocks Lindgren [44] assumes for clays and shales that capillary openings exist. He gives the lower limits of capillary openings as 250 microns down to 100 millimicrons but at the same time gives strong evidence from Baker that they may be very much smaller, in fact below 10 millimicrons. (This is based on twice seven times an average unit crystal, the limit of attraction given by Baker, which gives a figure of 7 millimicrons.) These figures are well within the ranges of those given in Table 2 for hypofiltration. They are in general rather higher than the range in the table, but few will doubt that compression, local restrictions and particle hydration can in places *reduce* the passages to a point where the rock can provide an impeding barrier and it must be remembered that effective pore size is less than actual pore size.

The constitution of a barrier is considered to vary with the metal it is required to impede. The epithermal zone barriers are commonly very much more incompetent, compared with the underlying host, than is the case in the mesothermal zone. The barriers will grade down from carbonaceous shale, through more pelitic or calcareous shale, to lava flows and finally possibly mere fracture capillaries may suffice to impede solutions. Examples of this too will be quoted in the suitable place. Thus the greater the penetrability of an ion the denser the barrier it needs to encounter to be deposited.

It is also considered that the sealing of the pores by deposition and the opening by the minor movements common during ore-formation may well be factors in forming new openings and conditioning and reconditioning barriers, particularly in the lower zones. A balance is thereby established.

It should be noted that there is no reason why the ore should actually be deposited close to the barrier. The competent host rock is to be considered as

[44] Lindgren: op. cit., p. 33.

the reservoir for deposition, and attention may once more be drawn to the fact that where the barrier is not perfect the effect is a differential, not an absolute one.

Finally, while discussing the permeability of the barriers, it may be recalled that Lindgren refers to impermeable barriers, "impeding" ore solutions, a contradiction in terms, by which he presumably meant the term impermeable as comparative only.

Observed Examples of Impounding.

The writer is dealing with the examples he has observed in an apparently illogical order, as they are chosen in chronological order and following the growth of the theory on his mind. For this reason also the Raibl and Mezica deposits occupy most space.

Mezica, Slovenia.—At Mezica (Meisa) in the northwest corner of Slovenia, not far from Bleiberg, lies a small lead zinc field characterized by rather widely separated sulphide bodies lying immediately beneath the Cardita shale, in the lower Triassic dolomite. This bed of shale undulates and the mine occupies several square miles beneath it, bodies being connected by adit levels running from valley to valley through the Carinthian Alps. The shale is remarkably free of dislocations, so much so that the lower dolomite is very free of water above the level of perennial streams whereas the overlying Hauptdolomite is so wet that a hole pierced through to it, even on a dome, yields copious water.

The fairly gentle folding is characterized by warps on two lines roughly at right angles which results in some domes and basins. The main lead zinc bodies are all located in domes and anticlines (Fig. 4).

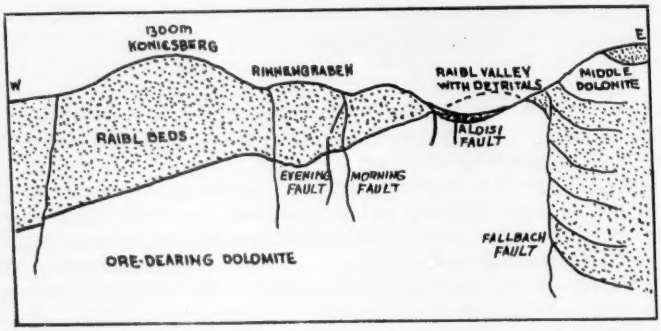
It could not be clearer that the loci of mineralization are at points which would be zones of complete and comparative stagnation to any circulation of solutions beneath the shales. They would however be the natural channels into which fluids that were impeded by the shale, but not completely arrested by it, would be guided.

Fuller details of the geology of this field are to be found in the writings of Posepny, Beyschlag and others, and in the writer's original paper [45] in which impounding was suggested in the present sense for the first time. These remarks apply also to the field that follows.

Raibl, Italy.—At the classic Raibl mine (now Cave de Predil) in the northeast corner of Italy, some 60 miles direct from the above, is a mineralogically similar occurrence which structurally offers an interesting contrast. Here the shales between the Lower and Haupt dolomite are known as the Raibl beds. They are up to 500′ thick and dip south at about 40°. It is crossed by dip faults and where the dislocation is complete or slight there is no big ore deposition. In the former case the barrier was destroyed and where there was free passage for solutions there is no mineral. In the latter the thick barrier was an obstacle to fluid. Where, however, the fault reduced the cover to about 50 to 100 feet two conditions were fulfilled. First, the

[45] Mackay: op. cit.

barrier being reduced made it the easiest way for the water to pass while providing adequate impedance to hold the metallic ions. Secondly, a beautiful channel was formed as illustrated in Figs. 2 and 3. Lest it be said that the second reason is enough the reader may refer to Lahnspitz valley where a splendid channel exists but where impedance was too great, and only small ore bodies formed. A solution would naturally be expected to choose the



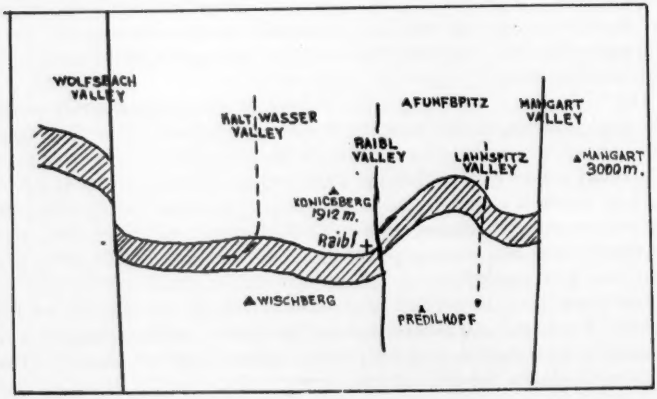


FIG. 2. Section across the Raibl Valley in the direction of the general strike. The strata dip south.

FIG. 3. Sketch map showing the parallel valleys in the Raibl district.

route of least impedance but where there is none at all, no separation can take place, as at Wolfsbach and Mangart. A repetition of the quotation from Locke [56] may be forgiven at this stage.

> The position of ore is not necessarily a question where the metal came from, for sources would be available over great ranges of structures. It is a question rather of traps which cause the metal to linger and concentrate on its outward journey.

Finally, a word of reconciliation with Posepny's views is desirable. He considered the parallel faults of small throw to be the control, for there lies the ore. The writer agrees that such faults were the actual channels embraced within the major structure, for the actual Raibl fault is of many feet of gouge, and itself a formidable barrier on that account, and certainly not a host-channel. Another point that requires to be exploded is Posepny's "stalactites" which he cites as evidence of the filling of large cavities. These peculiar hollow rods of galena in the order of 6″ × ½″ (as seen by the writer)

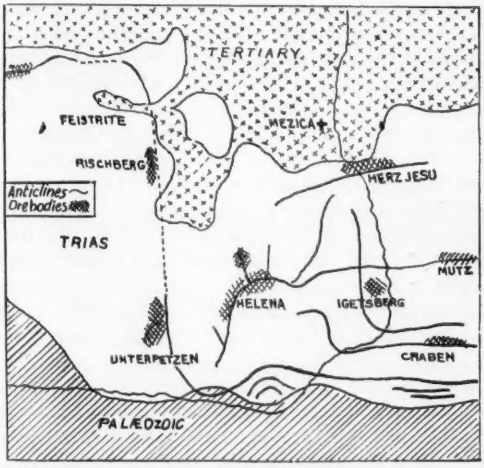


FIG. 4. Tectonic Map of Mezica.

are clearly formed on small intersecting fissures and are considered as evidence of host-solution preceeding deposition. The original paper gives other evidence that this took place.

It was earlier stated that the nature of solutions is not a necessary part of the argument of this paper, since it equally applies to colloids and true solutions. There can be little doubt however that at Raibl the solutions were colloids, a point which though now very obvious, was not then appreciated by the writer but which gradually dawned in the years following Boydell's writings.

Idria, Italy.—Passing to Idria quicksilver deposits in southern Udine, dolomitic limestones are overlain by shales and marls, and complex folding and contortion are present so that the influence of major structure is often obscured by the minor folds. Imposed on all this is overthrusting, and in a week's stay the writer found difficulty in mastering the structure even though good maps existed. It is however apparent that the thrusts and folds have made a vast variety of pounds. The cinnabar is in general not far from the marl or dolomite contacts though the reduced mercury (a favored ore) has

passed into the shales and the roots of the cinnabar veins and veinlets pass down into the limestones.

Cyprus, Copper.—In Cyprus there are excellent examples of barriers of marl, blanketing at low and very gently undulating angles, andesite in which cupreous pyrite bodies have been deposited in Tertiary time. Here no chemical fall of temperature or pressure, depeptization, intersecting fissures or other classic reason can possibly be introduced. The position below the marl of these bodies is the only plausible explanation of the cause of deposition. The marls are not fully conformable with the andesite but the period intervening was certainly very small, confined to the intrusion of a number of weak dikes that show evidence of consanguinity with the andesite and a few small fractures. Subsequent to the marl deposition, movement has been gentle and little faulting has taken place. Consequently, the blanket is still perfectly complete except where eroded. Owing to the low angles, careful mapping is necessary to demonstrate the rolls. This was done by the author at Kalavasso where the several bodies were found to be in a gentle anticlinal roll.

The comparatively great disseminated body of Mavoravouni is apparently the root of a body formed on a very gently pitching anticline. The main mine of the island, Skouriotissa, is on the flank of this anticline but the exact nature of the structure is not clear, and it may have been a now eroded gentle fold axis at right angles to the main anticline. No pyritic body ever entered the marl, but the mineralized envelope of the Skouriotisse body enters the rubbly marl-andesite contact which is a thin layer remaining on a part of basement conglomerate.

The lesson to be learned from these occurrences is in contrast to that at Idria. As would be expected, the less disturbed and folded the barrier, the less is the penetration into this barrier, for the greater is the area forming the impeding surface. It is interesting to note here that the author, asked in discussion by C. G. Cullis whether he thought impounding could have formed these bodies, replied by an almost emphatic negative. At that time his knowledge of these bodies was second hand and it was some long time later he worked on them. The original account had not given the picture of the pre-existing (eroded) structure, and the writer then thought the evidence of pounds was inadequate.[46]

Noranda, Quebec.—At the Noranda mine, a really beautiful structure is disclosed. The map published by Price [47] has been altered in shading and by the addition of a dip arrow, from the work of Connolly,[48] and observation of the author (Fig. 5). Both faults are thick with gouge.

The rhyolite is brittle and brecciated while *by comparison* the over-lying completely ore-free andesite is incompetent. If this faulted nose of a pitching anticline [48] is projected upwards the trap becomes complete. Now it will be noted that free passage for solutions through quartz-porphyry and rhyolite (which are not free of fractures) is conceivable to the north of the Horne

[46] Discussion at R. S. M. Mining Soc. meeting (unpublished).

[47] Price, P.: Geology and deposits at the Horne Mine, Noranda, Quebec. Canadian Mining and Met. Bull. 263, p. 108.

[48] H. G. Connolly: Of Ventures Ltd. in 1933. Personal communication from maps.

Fault. But yet these orebodies lie within the impeded passage way and not on the free route.

In this very perfect structure have been impounded iron, copper, gold, tellurides and minor zinc. Within this structure they have by no means conformed to the main barrier contact but have been influenced in immediate locus by zones of maximum brecciation, minor barriers, replaceable and irreplaceable rocks.[48]

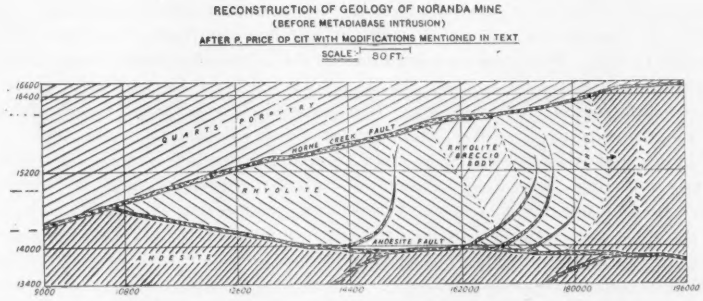


FIG. 5. Reconstruction of Geology of Noranda Mine (before metadiabase intrusion) after P. Price, op. cit., with modifications mentioned in text.

Further examples in Canada known to the writer could be given but they are examples to which the explanation probably rather than certainly applies, and it is sought first to show the more perfect examples that require no extrapolation or little deductive reconstruction. Some of them will be mentioned when dealing with the literature.

Goldfields in Tanganyika and Nigeria.—It is well known that there is a class of auriferous quartz veins which pass from granitic rocks to schists or shales and which tail off comparatively soon in value upwards and downwards from the contact. In Nigeria the writer has seen cases where veins of this type carry gold where situated in anticlinal rolls of the contact, but are barren away from such structures. In one case a host of small veins were in a structure where the granite-phyllite contact assumed the form of an inverted boat. Nearby quartz veins are valueless.

On the Lupa goldfield small lenses are scattered in a country consisting mainly of fairly small masses of various types of granite and metadiorite surrounded by granitic [50] and para-gneisses. Many structures are so small and local that interpretation of their pre-erosion nature is difficult or impossible. But loci such as the footwall of a diabase dike or the undersurface of a metadiorite were preferred by mineral, and this was quite out of proportion to the frequency of occurrence of quartz bodies.[51] In no case is the top of a meta-

[50] Grantham, D. R.: The Lupa Goldfield. Geol. Bull. 3, Tanganyika Territory, Geol. Surv., 1934.

[51] Mackay, R. A.: The history and development of the Lupa Goldfield. Transvaal, S. Africa, Chem. Min. and Met. Soc., 1936.

diorite the locus of a gold vein, and in only one case was one seen on the upper side of a diabase dike. In this case there are veins on both sides of the same dike, the top one having yielded ore down to about 20 feet only and the bottom one to over 100 feet. Ore shoots against the underside of pre-mineralization post-quartz faults or dikes were noted on the field, but not one converse case was seen.

Evidence in the Literature.

General.—The first paper that set the writer to consider impounding was by Hulin [52] and in the realization of the importance of structural control much is owed to him. For reasons mentioned in the acknowledgments many landmarks are unmentioned, but one that is recollected is by Derry,[53] who quoted many examples of anticlinal drags that have harbored ore in Canada, and shows how differences of competence control mineralization.

James and Mawdsley [54] have stressed that the copper bodies of Quebec occupy anticlinal belts, and further state that the gold occupies synclines, which they do not explain. But Derry's [53] suggestion that the anticlines have for the most part been granitized may well account for hypothermal deposits being in synclinal zones, for in numerous areas these are the only remaining weakness zones at hypothermal level. As mentioned above, Derry ties most of his examples to anticlinal drags within these synclines. A reconstruction from Todd's work (Fig. 6) is given in the present paper for the great Kirkland Lake break.

Newhouse [55] comes nearer to the present theme, when he quotes the influence of impervious roofs and damming of solutions. He considers a synclinal habitat to need special explanation. Newhouse considers that "There appears to be a pronounced tendency for solutions to rise within a structure." He uses the word "impounding," but does not develop the idea as to what happened to the solutions after they had risen within the structure to the impounded zone. It is certain that for deposition the fluid must have either passed down again (a peculiar form of circulation) or gone through the barrier which it had been at such pains to seek out. An excellent bibliography is included within this comprehensive paper which is relevant to the present theory.

More recently, Locke [56] has stressed the same principle:

> The position of ore is not necessarily dictated by where the mineral came from, for sources would be available over great ranges of structures. It is a question rather of the *traps* which cause the metal to *linger* and concentrate on its outward journey. . . . These traps are part of the tectonic pattern (italics by writer).

Finally the cupolas of Emmons [57] are but large scale impounding structures. But Locke may be nearer the truth than Emmons as to why they are the loci of ore.

[52] Hulin: Structural control in ore deposition. ECON. GEOL., 1925.
[53] Derry, D. R.: Structures in Canadian early Pre-Cambrian shield. Q. J. G. S., 1939, vol. xcv, p. 109.
[54] James and Mawdsley: Misc. Publ. Geol. Dept. of Quebec.
[55] Newhouse: Some relations of ore deposits to folded rocks. T. A. I. M. E., 1931, p. 225.
[56] Locke, A.: Granites and ore. ECON. GEOL., 1941, vol. xxxvi–4, p. 448.
[57] Emmons, W. H.: Relations of metalliferous lode systems to mineral deposits. T. A. I. M. M. E., 1926, p. 29 (and elsewhere).

Mercury.—To turn to examples where impounding structures are deemed to be a prime cause of deposition, it is but natural that the finest examples are in mercury deposits, for the last of the common hydrothermal metals has been deposited close to existing surface, whereby the structures are still easily interpretable. Schuette,[58] in a paper which Lindgren greatly commended, evolves for quicksilver a theory of "primary concentration by traps" and says "the proper trap structure must be present before an ore-body can be formed."

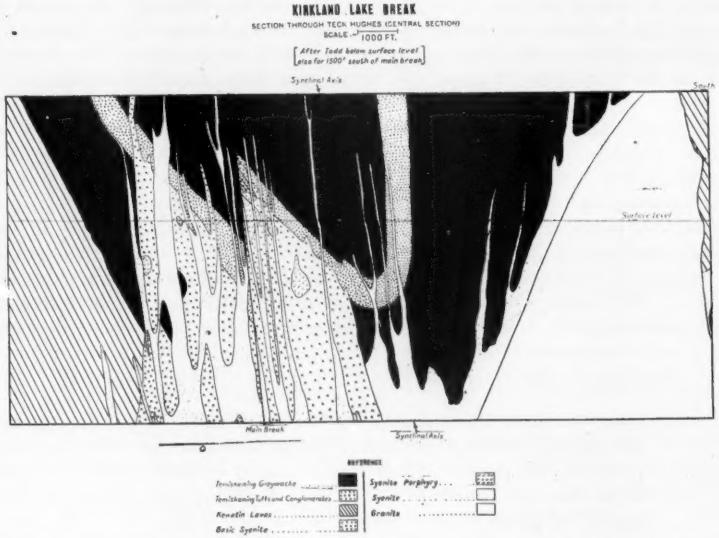


FIG. 6. Kirkland Lake Break. Section through Teck Hughes (central section). (After Todd below surface level also for 1500′ south of main break.)

"The hanging wall is generally a *clay gouge* or other *relatively* impervious rock" (italics by present author). He adds that "the porosity generally determines the grade of an ore," introducing the host reservoir theme. He regards the solutions as "directed, limited or dammed" by the trap and uses the nice simile "an inclined gutterpipe bottom side up."

The present author considers the last two functions are fully explained by Mezica and Raibl and thinks for reasons given later that the subsequently postulated explanations of cooling, loss of pressure or chemical agents are totally inadequate as applied at points where circulation has been limited or dammed; surely a virtual contradiction of terms? Among the traps[59] Schuette quotes are: a basalt cap just prior to mineralization, at Oat Hill (indeed a complete barrier); at Chisos, marl and shale over limestone, pre-

[58] Schuette, C. C.: Occurrence of quicksilver deposits. T. A. I. M. E., 1931, p. 403 and p. 409.

[59] Schuette, C. C.: op. cit., p. 421 et seq.

sumably domed; a shale overlie is faulted by a "mudfissure" at Pershing mine, giving a complete trap; Opalite mine in Oregon has a double trap of a mound-like low-grade siliceous sinter flanked by lake beds, and beneath this is a lava which in turn overlies a crush zone in coarse intrusive holding good ore. In addition to the United States Schuette [60] quotes instances in Mexico, Peru, Italy, Spain and Russia.

Lead-Zinc.—Lead-zinc deposits provide the next clearest instances, being next in ease of geologic interpretation and depth. Mackay,[61] as far as his search of the literature determines, provided the first paper where impounding was deemed the prime cause of any orebody, and not an incidental in choice of locus of deposition. Two of the fields have been described briefly in the present paper. He also quoted a dome in Derbyshire, England, and impounded ores in Morsenet, Germany. Subsequently, Schnellman [62] decided that "ponding" below shale was a control at Halkyn, England. The ponds were upside down, and the actual cause of deposition tentatively held to be temperature fall or depeptization at points where evidence of quick cooling or release of pressure was contra-indicated. The word "ponding" seems to have been used before Schnellman in a paper to which the writer has not had access and which Schnellman omitted to record.[63] But Schnellman's paper is a gem of descriptive work and of the application of the best of the Economic Geologist's trade. It clearly showed the mineralization to lie beneath dome-type shale structures in limestone.

Schnellman's descriptive work brings out the following facts well:

(1) That the first "impermeable" bed may not suffice completely to hold the mineral, but that ore bodies below successive barriers above are progressively poorer. Only in the case of comparatively great fractures does ore penetrate so far as to lie below the largest, or third barrier of shale.

(2) Gougy cross faults have an equally impeding effect as have shale beds and ore occurs within the apex of such structures.

(3) A stratum contour tracing of the overlying shale, showing "crest-lines," perfectly fits the locations of the orebodies.

(4) Upwards of any kind form loci. In recognizing this he acknowledges the aid of H. J. Connolly from whose stimulating mind the present author also benefitted when in Canada.

Other examples of blanketed lead and zinc are indeed numerous.[64] Leadville, Colorado; Bawdwin in Burma, where tuffs are overlain by sediments; and the Rice dome below semi-permeable shales as in Lindgren's type-example.

[60] Schuette, C. C.: op. cit., pp. 449–481.

[61] Mackay, R. A.: The influence of superimposed strata on the formation of certain lead zinc ores. T. I. M. M., 1925.

[62] Schnellman, G. A.: Applied geol. at Halkyn District Mines. T. I. M. M., 1939, p. 685.

[63] Bain, G. W.: Mechanics and metasomatism. ECON. GEOL., vol. 31, p. 505.

[64] Emmons, Irving and Loughlin: Geology and ore deposits of the Leadville district. Prof. Paper 148, U. S. G. S., 1927.

Copper.—The author knows of no paper where impounding is directly applied to any class of copper deposits. However, of the Michigan deposits, Lindgren [65] says, quoting from Butler, Burbank and others, that the ascending thermal waters rose beneath the impermeable barrier of the next overlying flow and deposited its load beneath such flows. The major fault to the east most likely completed the trap.

The Namaqualand copper bodies [66] are another illustration, where the orebodies are intrusives into metamorphic rocks, which in the area containing the copper deposits, are disposed in the form of a great dome.

Gold.—In the case of gold, Wisser [67] has given two excellent examples where he regarded trapping as the direct control. In both cases the mineralized areas would seem to have been zones of stagnation to the normally conceived system of solution circulation. One is at Hog Mountain, Alabama, and the other at Paracale in the Philippines. These two very different types of deposit have impounding given as the main control. This paper is an excellent example of the theory.

To take the complex case of Kirkland Lake. There was little evidence of any impounding structure at the surface, in fact on the central section of the Kirkland Lake "break" there was none. However, the thorough mapping and correlation presented in Todd's paper [68] has made possible a reconstruction which shows quite clearly that impounding was a probability of high degree. Fig. 6 is based on Todd's generalized section No. 37e, projected upwards using the following assumptions:

(1) That the basic syenite has reached its maximum development at existing levels. For justification of this, Todd's sections Nos. 37c in particular 5, 13, 14 show it much reduced at present surface and others, of the same series No. 37c, show it being terminated before penetrating the tuffs, except in his generalized section No. 37c–6 where comparatively small tongues extend some distance upwards.

(2) The main body of syenite and syenite-porphry complex is giving way to upward penetrating tongues of decreasing strength and number. Sections Nos. 37c–6, 2–5, and 7 indicate that this is the case as do the block diagram and surface interpretation maps.

The section here produced through the central section discloses the tuff-greywacke cover as likely to have existed over a less incompetent intrusive mass, which latter made a wedge-shaped indentation in the north flank of the syncline.

A cover of this shape and constitution would certainly impede rising solution near its base. The hinging of the fault and the disposition of the intrusives make the structure best defined on the central section. To the west the igneous core of the structure pitches down, and to the east, owing to the break-up of the main fault, it loses its definition. (See Todd's plan 37e.)

[65] Burbank and Butler in Lindgren: op. cit., p. 524 and Fig. 206.
[66] Dept. of Mines of S. Africa. The Mineral Resources of S. Africa, vol. 136, p. 192.
[67] Wisser, E.: Geologic parallels. Econ. Geol., May, 1939.
[68] Todd, E. W.: Ont. Mines Dept. Annual Report, 1928, vol. xxvi, pt. 2.

The mineralization responds by pitching to the west and losing its regularity and intensity to the east.

Other examples which the theory would fit, but to which the authors have not applied it are[69] the Omega mine, Ontario, and the Camp Bird, which from the diagram quoted should be an absolutely impassable compound trap for heavy molecules.

Tin Suite.—Coming to the tin suite of minerals, these are accepted as associated with the tops of granitic domes, or cupolas, by many writers, in particular, Emmons.[71] The classic source is the granite. The classic interpretation for deposition is fall of temperature. It is not the purpose of this paper to contest the former, but as it has its doubters in Brammal,[72] Locke[73] and others, it may be noted that, whether or not the doubts be sound, here at least is explanation for the locus.

The inadequacy of temperature fall and pneumatolysis have been dealt with. In the case of tin, temperature fall is particularly inadequate as its large solubility should at least in part take it into far cooler zones, whereas, with the exception of Bolivia, it is firmly attached to the lower zones. Now on the penetrability postulate it is among the least penetrable and is therefore held up by the least perfect barrier, which may consist of comparatively large pores or fissures. An anomaly such as that of Bolivia therefore becomes no anomaly if tin, or any other metal, reaches a higher zone before encountering a suitable trap. Normally the more penetrable metal will travel further but several may encounter a barrier which they cannot penetrate at one time, resulting in the numerous zonal anomalies that have exercised the minds of Lindgren,[74] Spurr,[75] Hewett,[77] Garrels[78] and others which caused Spurr to postulate his "telescoped" deposits.

Miscellaneous.—It is possible that where telescoped deposits occur there may be very thorough impounding indicated, as in the case of the Tertiary volcanics overlying the Mesozoic limestone as an anticlinal fold over the Peñoles vein-system, and the excellent traps provided by the lacework of Tonopah faults. At Tintic also the trap is likely to have been very complete prior to the post-mineralization faults.

Finally, to consider the converse of impounding. Tungsten is a recognized hypothermal mineral, but it reaches the surface in large quantities in hot springs at Uncia, Bolovia.[79] One can only assume that, as with other less extreme cases[80] of hot metal-bearing springs, no efficient barriers impede their progress, and there was no point of a concentration of deposition.

69 Jenny: Geology of the Omega Mine, Larder Lake. Econ. Geol., vol. xxxvi, p. 423.
71 Emmons: op. cit.
72 Brammal, A.: Misc. public. and unpublished lectures, 1937.
73 Locke: op. cit.
74 Lindgren: op. cit., p. 121.
75 Spurr, J. E.: The Ore Magmas. McGraw-Hill, 1923.
77 Hewett, D. F.: Zonal arrangement of lodes in Lumpier Quad. T. A. I. M. E., 1931, p. 305.
78 Garrels: Mississippi Valley lead zinc deposits and the problem of mineral zoning. Econ. Geol., 1941, No. 7, p. 729.
79 Lindgren: op. cit., p. 121.
80 Clarke: Data of Geochemistry, pp. 183–185.

CONSIDERATIONS ARISING FROM THE THEORY.

Comparison with Other Theories of Deposition.—There are many reasons advanced for the cause of deposition and there is no doubt each has its place in special instances. Chemical environment and changing temperature and pressure conditions doubtless contributed to the locus of deposition. But the universally applied fall of temperature (and pressure) as the *major* cause has always seemed singularly inadequate and overstated.

The well known series of change from tin (tungsten ?), copper, zinc, lead, quicksilver, of which (excepting Hg) Cornwall is the classic example, is incomprehensible on such a theory; deposition of one salt from a mixed solution during falling temperature does not almost suddenly cease and give place to another, but is gradual right down to atmospheric pressure and temperature, and is collaterally with other constituents. Less still does the most soluble salt deposit earlier than less soluble ones.

Only by repeated fractional crystallization can the predominance of one salt be obtained. The writer has never seen any convincing attempt at explaining why an ore solution (or an aquo-ore system) should deposit its *insolubles* such as lead and mercury at a late stage and its *solubles* such as tin or zinc at an earlier stage.

Spurr [81] has found it necessary to say that if a hot mineral solution reaches surface, "for some reason" ore deposits do not form. It is interesting to note at this point that where such solutions do reach surface they commonly contain metals of widely different zones, sometimes near saturation point, though in very dilute form. The reason here advanced is that free passage having been allowed no sustained deposition can take place.

An acceptance of the postulate of this paper makes comprehension fairly easy. Deposition cannot take place without impedance except in small amounts of mixed minerals. Impounding is necessary to hold up appreciable amounts of hydrothermal minerals and separate the more easily from the less easily impeded metals.

Stated differently, either the temperature or pressure curve for a solution finding its way to surface is of the type of Fig. 7. Now, in a cooling solution the steeper the curve the greater the rate of deposition of a salt, and there cannot be the slightest doubt that (after the solutions have been ascending for a while) the exodus is on the steepest part of the curve, and the same is true of pressure. It is in nature observable that there is an increased amount of deposition at these exodi but at none of them has there been any deposition commensurate with even the smallest orebodies. Thousands of tons of material are deposited but it is of mixed nature and in general of the small (penetrating) gangue molecules.

Many geologists have postulated the same question as Spurr,[82]

> Why do not solutions appear at the surface, and there form ores of unparalleled richness? The fact that they do not leads to a strong assumption that they cannot. Why can they not? It is hardly a question of temperature, for volcanic fumaroles are in part very hot.

[81] Spurr: The Ore Magmas. McGraw-Hill, 1923, p. 298.
[82] Spurr: Idem.

His "oremagmas" seems an untenable answer as *some* of such magmas must have burst through, had they existed. The logical answer seems simply that they cannot because they are impeded. If they were not impeded they would be widely dispersed and no mineral formed.

Further it is incontrovertible that if hypofiltration can take place in a geological environment it must be capable of concentrating more mineral in a given structure than fall of temperature or pressure could do. For fall of temperature and pressure cause a quantity of deposition proportional to their change of magnitude, so that a solution would deposit only that portion of its solute at a given place which was commensurate with the temperature-pressure changes that took place there, passing on elsewhere with the balance of its load. On the other hand hypofiltration would, subject to the degree of perfection of the barrier, remove all the solute. This as an argument for impounding is admittedly indirect, but to the writer it seems admissible, for it reduces prodigiously the necessary volume of solution which must have passed and this enormous volume required by the older theories has always been such that (due to their finding it difficult as a conception) leading writers have sought in new theories, to explain it away. Examples of theories which have aimed at explaining away these volumes are Boydell's theory of almost-universal colloidal deposition and Spurr's theory of ore-magmas, both of which have had to be rejected in their full application on various grounds.

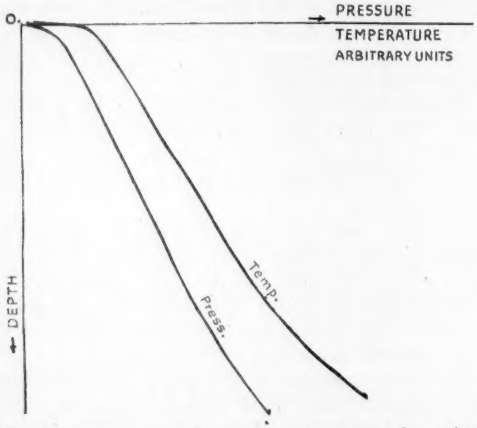


FIG. 7. Fall of temperature and pressure on ascent of a solution through permeable channel.

Finally, we may discuss Fig. 8, which gives a pictorial representation of the passage of solution through a series of shales and limestones. Passage of true solution through the former would be in restricted channels and there would be a damming effect before them. On discharging into the upper limestone, restriction would cease and a wider path be taken resulting in more rapid fall of temperature and pressure.

From this it will be seen that on the theory of fall of temperature and pressure concentrations *above* barriers or restrictions would be expected, whereas in nature concentrations are almost invariably below them, which is as it should be only if impedance has been effective.

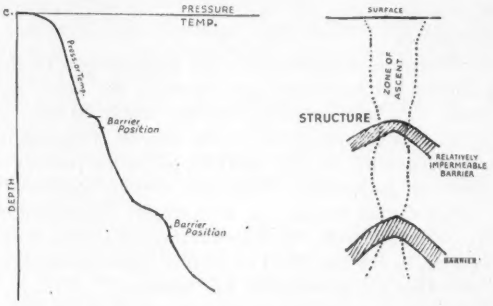


FIG. 8. Postulated fall of pressure (or temperature) on ascent of solution in an impeded structure.

Another theory that has been advanced by a number of writers, largely to explain the deep tin suite, which was popular twenty years ago, is pneumatolytic action. A decade ago this began to find disfavor with leading authorities and Lindgren may [84] be quoted on the subject:

> What part the critical phenomena play in these solutions is not well known. On one hand there are many fluorides and chlorides in which the critical temperature is relatively low—not much higher than that of water. But it must be remembered that these haloid salts are only parts of the solution which must contain an abundance of salts with exceedingly high critical points. Among these constituents the most important is silica which, it would seem, must be carried in colloidal condition. The evidence tends to prove that the solutions are liquids rather than gases and that "pneumatolytic" conditions (if by this much abused term is meant solutions above their critical temperatures) play no important part. Therefore, the term *pneumatolytic* will be avoided in the following discussions.

Bowen in his petrological masterpiece [85] has dealt devastatingly with the influence imputed to volatiles, which, while not entirely decrying, he places on sound physical chemical grounds in its proper perspective. His remark that, "To petrologists a volatile component is exactly like a Maxwell demon; it does just what one may wish it to do," may with greater force be applied to one period of writing on ore genesis.

Contradictions and apparent loose thinking among fine scientific minds is indicative of one thing only, that unknown factors have been omitted. Parallels can be thought of in physiology where valiant but erroneous theories have been advanced to explain processes that could not be explained until physical chemistry or electricity had advanced, or the physiologist had applied the

[84] Lindgren: op. cit., p. 117.
[85] Bowen: op. cit., p. 282.

more recent advances in one of these subjects. These partially or wholly erroneous theories have often been useful in their time as a basis on which to build, and if the present theory proves to have its errors the author does not apologize for its advance.

In the writer's opinion, the unapplied factor in hydrothermal deposition is hypofiltration, comprehending (as explained under Physical Chemistry) ultrafiltration and osmosis.

The Rarer Hydrothermal Metals.—The development of the penetrability aspect of the theory has been largely confined to the five commonest hydrothermal minerals. To have considered all the metals at once would have resulted in difficulty of presentation due to the volume of discussion necessary in the section on penetrability through barriers, for in the present state of knowledge there must be anomalies. First, as already explained, a numerical penetrability series cannot be devised, and second, consideration of the complicated matter of the lyotropic influence on the anions has been advisedly deferred in this paper, as has the effect of type of chemical binding. Some consideration of the other metals is called for, however.

Listing all the metals not so far dealt with, which are included in Emmons' paper,[86] in order of the ionic radius (given in brackets [87] where from reference and double brackets where estimated), we have:

Barium (1.53). This conforms in penetrability with observed fact as to its high position.[87a]

Gold (1.37). This conforms for the epithermal gold zone, but its method of carriage must be more fully understood before its hypothermal phases are understood. It is unlikely it is comparable with the base metals.

Silver (1.26). In general its penetrability is high but is not quite as high as would be expected from its ionic volume *and* atomic volume. This is perhaps not surprising because silver has completely anomalous behavior as regards its hydrating power, ionic volume and ionic velocity 326J.

Bismuth (0.98). On ionic volume its zone position is reasonable. Allowance for its high atomic weight might however seem to result in over compensation.

Tungsten (0.96). The ionic volume coupled with a very high molecular weight reasonably accounts for its low zone position.

Arsenic (0.71). The low ionic volume accounts for its usual low penetrability. The low molecular weight accounts for its passing above tin. That it also sometimes passes into higher zones may be connected with unknown complex anion influences.

Antimony (0.89). This metal is quite out of position. The writer puts forward no explanation at present. The solution may lie in its amphoteric nature, but amphoteric arsenic appears in a reasonable position as does the anion wolfram.

[86] Emmons, W. H.: Primary downward changes in ore deposits. T. A. I. M. M. E. E., 1924, vol. 70, pp. 964 and 992.

[87] Rice: op. cit., p. 220, Table 16.

[87a] Jones: op. cit., p. 326.

There are also a number of metals not included in the Emmons zonal suite, which have hydrothermal affiliations in the wide sense. Where the ionic radii are available they are placed in brackets after the metal. Where they are not an estimate is given, from interpolation, in double brackets.

The concentration of the undoubtedly low penetrability metals beryllium (0.43) and lithium (0.59) in the pegmatite zone is of interest, as is the fact that the platinum metals have a very low ionic volume for their atomic weight. These fit well with the general theory, but if they are included cerium (1.27) must be quoted as an exception.

The behavior of cobalt and nickel ((0.7)) is not understood. The position of the sub-magmatic Sudbury Ontario deposits agrees with an expected low penetrability but the Schneeberg, Saxony, and Cobalt, Ontario [88] type is less easy to understand on account of the associated silver. A "telescoped" deposition may be the explanation.

The position of iron ((.70)) may call for explanation but the maximum development of pyrite is mesothermal, to which zone it would be expected to penetrate. Its certain association in a number of different ionic forms may well account for its ubiquity as regards penetration. Further research is certainly necessary on it and other gangue minerals.

From these metals, which are difficult to discuss because of gaps in the geological as well as the physical data, the following generalizations emerge:

(1) If two metals of defined position in the hydrothermal suite are out of position relative to one another in the ionic volume series, the atomic weight of that higher in the latter will be found to be greater than the metal towards it presents anomaly. The only exceptions are zinc (and cadmium) and antimony.

(2) In a horizontal row of the periodic table, any metal shows greater penetrability than that next to it in the direction of a greater number of electrons in unfilled shells. Antimony is an exception and zinc is an exception, these having been already cited as such and discussed.

(3) In any valence group of the periodic table which has an equal number of electrons in the outer shells, the metal lowest down the table has the greatest penetrability. Exceptions are nickel-cobalt with respect to iridium and platinum, vanadium to tantalum (?). Three of the last four metals are not truly hydrothermal and the last two presumably travel as anions.

Summarizing, the penetrability series cannot be mathematically worked out, but certain rules apply to all the metals except that those behaving amphoterically under hydrothermal conditions, and zinc, do not completely conform. All occupy a position in nature which is reasonably consistent with, and in most cases positions in complete accord with, the application of penetrability to this impedance theory. For there to be no exceptions would mean that no other chemical or physical influences had been at work, and would also entail

[88] Lindgren: op. cit., pp. 602 and 603.

complete understanding of the lyotropic influences. The first of these provisos is by no means contended and the second far from accomplished.

Finally the author draws attention to the fact that he has deliberately omitted from this paper much discussion of the anions. This is because, first, the mode of travel is still in some doubt, and secondly, the lyotropic nature of the anions is less advanced than in the cases of the cations. It would seem, however, that if the same principles are applicable to anions, SO_4 would be more penetrable than S, and S than OH. It is not proposed to elaborate the significance of this but those who have followed the full argument of this paper will see that study of anion influences will be likely to strengthen the series and perhaps even explain the oxide to sulphide zoning.

The Relation of Impounding to Replacement.—This section and the one that follows are on a more tentative basis than that which has been discussed hitherto. Notwithstanding the fact that in the present state of knowledge there is much requiring further elucidation, the writer considers that nevertheless the influence of impounding is incontrovertible, and a tenable theory has been advanced to explain it. In the case of what follows he merely submits that there is a case to answer.

Where a cation in solution under pressure meets the cation of a solid mineral having greater penetrability, it seems likely, on the principle of Le Chatelier, that the first should replace the second. This should be accentuated if the channel through which the solution is passing is dense enough to provide appreciable impedance to the replacing solute, or if there is a more incompetent or dense rock above. Conversely if there is no impedance of the solution, there should be no replacement in any case where the solution and mineral do not react under known physico-chemical conditions. The mystery surrounding replacement of one mineral by another with which it has no known reaction has so far often defied explanation. The role of diffusion in the actual mechanism of replacement is not contra-indicated by this conception of replacement. The explanation proposed in the preceding paragraph is of a nature that could be tested in a fully equipped geophysical laboratory.

A few examples only will be quoted.

Sodium definitely has lower penetrability than potassium.[89] Can this account for albitization? In fact are albitization, sericitization and propylitization themselves to some extent a zoned series dictated by the penetrability of the alkalis and alkali earth metals? Gallagher [90] has shown that the albitization connected with gold is generally hypothermal or lower mesothermal, whereas increased potash is associated with higher zones. His remarks on tin-suite wall-rocks do not entirely fit this thesis but the writer thinks there is an explanation for this which is outside the scope of the tentative nature of this section. If there is such a thing as impedance zoning of alteration, it would not rigidly follow the temperature zones but be determined by geological factors. The generalizations quoted here from Gallagher are however very significant at this stage of the theory as applied to replacement.

[89] Freundlich: op. cit., p. 747.
[90] Gallagher, D.: Albite and gold. ECON. GEOL., 1941.

Magnesium is probably less penetrative than calcium. Could regional dolomitization ever be so caused?

Silicification is too widespread to be considered in the first review, particularly as many consider it is commonly colloidal. Silica is probably often an *early* colloid. Reverse instances may be thought of and there is no doubt that many are the causes of replacement. However some of the cases of hydrothermal replacement which are among the more difficult to explain, may tentatively be explained by impedance, particularly in cases where mass action or double decomposition fails to explain the replacement.

Other Structures to Which the Theory may Apply.—The author puts forward these structures with which he is not familiar very diffidently, for the consideration of others. It is not contended it does apply to them. They are queries.

The varying dehydration of oil lying in different reservoir formations deserves consideration. Here the size of the molecule may well have prevented the oil from passing a barrier that would pass water. Where, however, the water is saline it does not always pass. Sometimes, however, the water has parted from the salt and a salt dome is left. If the theory is to apply, the barrier should be very complete, for though the ionic volume of sodium is high, its molecular weight is low, and it is univalent and therefore its place is fairly high on the penetrability series. There should also be evidence of higher pressure having existed (without rupturing the barrier), than where saline solutions exist.

It may also conceivably be possible that descending meteoric solutions act in the same way. Hematite, formed overlying a semi-permeable bed as in Cumberland, England, is a case in point. Here it would need that the competent superimposed host was very open, capable of allowing a hydrostatic pressure greater than the osmotic pressure of the iron solution, whatever form that solution may have taken. A carbonate for example would have a very low osmotic pressure. A more doubtful possibility would be the existence below the barrier of a solution of higher osmotic pressure. Solution contact having been established, osmotic action would exceed the potency of hydrostatic pressure. (Endosmosis and not exosmosis would be the phenomenon involved.)

CONCLUSION.

The metals are held to have ascended in solution and been impeded zonally, according to their powers of penetration at barriers of decreasing effective pore size. Not all, or necessarily several, zones will be represented in any sequence, but for each metal there is a degree of impedance necessary to impound it. For the hypothermal minerals relatively little impedance is required; for mercury, a very fine and complete barrier is essential.

The value of a theory lies not in its being an ultimate truth but in its ability to predict or explain experimental facts, in this case field observations. Does this theory fulfil this function? The writer submits that it explains adequately the locus of hydrothermal ore deposits where the containing structure is intact or capable of interpretation, and that it explains, or at least advances a

sound reason, which can be further worked out, for the zoning and position of the metals. As regards prediction he believes that the theory, which correlates the work of past observers, will provide a basis for ore search which may become as valuable as the anticline or dome was to the oil technologist.

ACKNOWLEDGMENTS.

This paper has been written entirely in West Africa and mostly in the bush. The small library of the writer and his notes therefore place considerable limitations on the references. He therefore apologizes if the work of others has been anywhere overlooked.

The work of Mr. E. H. Jaques of the Nigerian Geological Survey is gratefully acknowledged for reading and helpful criticism and to Dr. H. Vine of the Agricultural Department of Nigeria much is due for his aid in presentation of the Physical Chemistry.

Above all, and this is as much a dedication as an acknowledgment, I am indebted to Sir Thomas Holland for his belief in the value of the theory and his encouragement many years ago when it was in a much cruder state than it is now.

IBADAN, NIGERIA,
Nov. 13, 1945.

[91] Garrels, R. M.: ECON. GEOL., Nov., 1944, p. 472. The means of replacement by colloids is discussed here. This paper came to hand after the above was completed. It also stresses the anomaly between distance of transport and solubility.

HUMIC ACIDS AND TRUE ORGANIC ACIDS AS SOLVENTS OF MINERALS.

WALLACE G. FETZER.

ABSTRACT.

A survey of the literature reveals assertions that the humic acids are active solvents of minerals. Indeed, it has been said that they will dissolve gold and even platinum. This paper describes experiments which were made to check the validity of these statements. Humic acids were isolated for this purpose, and the conclusion reached is that they are ineffectual. So that the reader may better see the reason for this, observations are made pertaining to the chemical characteristics and colloidal nature of humic acids. It is also concluded that humic acids are not acids in the usual sense of the word, and that a distinction is to be drawn between them and the true acids. Inasmuch as the latter are invariably associated with humic acids, the paper further describes solubility experiments using representative true organic acids. In contrast to humic acids, they were found to be effective solvents.

Through hydrolytic exchange adsorption, humic acids in contact with salt solutions are able to liberate free acids. Experiments indicating that acids of this origin may sometimes act as solvents are also described.

The minerals dealt with are calcite, metallic gold and copper, and some of the more common compounds of silver, copper, zinc, manganese and iron. For experimental convenience, synthetic compounds were used in some of the investigations.

INTRODUCTION.

IN 1934, prompted by F. W. Freise's experiments,[1] indicating that humic acids will dissolve gold, a discussion describing some of the present writer's efforts to verify this phenomenon appeared in this journal.[2] The results of 75 individual experiments made up to that time were entirely negative; however, the properties that Freise attributed to the humic acids were so unique that the experiments were continued and expanded to include the solvent effects of some of the better known organic acids on minerals.

ACKNOWLEDGMENTS.

The experiments described in this paper were performed at the University of Minnesota; and the writer wishes to thank Dr. J. W. Gruner, Dr. L. H. Reyerson, Dr. G. M. Schwartz, and Dr. George A. Thiel for their gen-

[1] Freise, F. W.: The transportation of gold by organic underground solutions. ECON. GEOL., vol. 26, pp. 421–431, 1931.
Freise, F. W.: Metall und Erz, vol. 27, pp. 442–445, 1931.
Freise, F. W.: Chemische Processe Bei Bildung von Seifenlagerstätten. Zeitschrift für praktische Geologie, vol. 7, pp. 97–103, 1932.

[2] Fetzer, W. G.: Transportation of Gold by Organic Solutions. ECON. GEOL., vol. 29, pp. 599–604, 1934.

erosity in supplying materials and the privilege of discussing certain phases of the problem with them. The writer is indebted to Dr. W. H. Emmons for suggesting the attempted verification of Freise's original experiments on the dissolution of gold by humic acids.

THE CHARACTER OF HUMIC ACIDS.

Inasmuch as it is extremely doubtful that humic acids are acids in the usual sense of the word, it seems fitting that their properties, as observed by the writer and others, be recorded here as this misnomer may lead to assigning false attributes to them.

The name "humic acid" originated with Wackenröder,[3] who treated Gestewitzer coal (lignite) with sodium carbonate and obtained 22.5 per cent by weight of a dark brown amorphous substance by acidifying the resultant solution. The foremost investigators of the humic acids have been in the fields of fuel and soil sciences and colloidal chemistry. They unanimously agree that humic acids are understood to be a dark brown substance of turf, peat, or lignite that is dissolved in alkalies and reprecipitated by mineral acids; and, that they are *insoluble in water*. According to the most widely accepted theories, they are formed by the natural decomposition of lignocellulose. Generally the name is pluralized as they are definitely known to be a variable mixture of many different compounds.

For the experiments described in this paper, the humic acids were extracted from peat and lignite by the procedure previously described by the writer;[4] and, as humic acids have a great power of adsorption, they were then purified by electrodialysis in order to distinguish between the possible effects of adsorbed impurities and those of the humic acids themselves. At the end of purification, the specific conductivity for a 2.60 per cent humic acid hydrosol as taken from the electrodialyzer cell was .002150 reciprocal ohms. At different dilutions with conductivity water, the specific conductivity in reciprocal ohms of the same humic acid sol decreased as follows: 1.30 per cent humic acid, .0001122; 0.65 per cent humic acid, .0000654; and 0.32 per cent humic acid, .0000493.[5]

Some electrolyte, undoubtedly, remains adsorbed by the humic acids in small amounts even after electrodialysis. In addition to this impurity are those inorganic constituents of peat and lignite which are soluble in alkali and insoluble in water and in the acid used in precipitating the humic acids. These, being precipitates, do not respond to dialysis and, therefore, cannot be removed by this procedure.

After dialysis the humic acids are in a very fine state of dispersion. They will pass through the finest filter paper; and can only be separated from the liquid in which they are peptized by ultrafiltration or by flocculation.

[3] Berzelius: Jahresberichte, vol. 30, p. 487, 1851. Knapp, W.: Deutsche Braunkole, vol. 1, a/S, 1915.

[4] Fetzer, W. G.: op. cit.

[5] The concentrations are given in per cent of dehydrated humic acids. The sols were evaporated and dried at 80° Centigrade for 24 hours. The measurements were taken at 25° Centigrade with a conductivity cell equipped with unplatinized platinum electrodes.

Acidity. According to the common concept, an acid is a compound which in aqueous solution (1) tastes sour, (2) changes blue litmus to red, (2) dissolves certain metals liberating hydrogen, and (4) reacts with metallic hydroxides—the hydrogen of the acid exchanging places with the metal of the hydroxide. In terms of the more specific definition based on the theory of ionization, an acid is a compound that (5) yields hydrogen ions in solution.

Obviously, to fulfill all of these conditions in an aqueous solution, humic acids must first be soluble. As traces of alkaline humates can be detected colorimetrically, a small amount of the supernatant liquid from the electrodialyzer was made alkaline with KOH and compared with distilled water. As a check, the same test was made on the dispersion medium of the purified humic acids which had been flocculated with a small amount of acetic acid. In neither test were the humic acids found to be even slightly soluble.

(1) Several persons declared that the purified sols prepared by the writer were tasteless and had none of the sour taste which can be detected in true acids even in very dilute solutions.

(2) A highly concentrated humic acid sol can turn a dry piece of blue litmus paper red; but, if the paper is wetted before being placed in the humic acids, the change in color is barely perceptible. This change of color cannot be interpreted as proving that humic acids are true acids. The same effect can be obtained with fuller's earth and similar colloidal substances which in no sense can be classified as acids. The change in color is due in reality to the adsorption of the base from the indicator by the colloidal humic acids. Humic acids are highly hydrophilic; and the red color produced by placing dry litmus in contact with them is more pronounced because of the imbibition of a part of the micellular water by the unfilled capillary pores of the paper, promoting a more intimate contact between the adsorbent surface of the humic acid micells and the indicator.

(3) As far as could be determined during this investigation, purified humic acid sols react the same as pure water does with metals.

(4) Humic acids appear to simulate a true acid only in their behavior toward metallic hydroxides. Some authorities say that they form humates and hydrogen ions in strongly alkaline solutions.[6]

(5) Being insoluble in water, humic acids cannot yield hydrogen ions in solution. This was verified by tests made on the supernatant liquid resulting from the cataphoresis of the humic acid sols during their purification by electrodialysis. It was nonelectrolytic, colorless, tasteless, and had a pH of 7 (neutral).

It is to be concluded that if humic acid hydrosols do possess acid properties, they are very feeble; indeed, the acidity reported by others probably is due to exchange adsorption and to small amounts of carbon dioxide formed by its oxidation. In accordance with this interpretation, other investigators have also attributed the apparent acidity of humic acids to the strong adsorption of cations.

[6] Ostwald, Wo., and Rödiger, W.: Studien zur Bodenkörperregel. Kolloid-Zeitschrift, vol. 49, pp. 314–321, 1929.

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EXPERIMENTS WITH GOLD IN HUMIC ACIDS.

Following the publication of the discussion of the writer's first attempts to verify Freise's experiments on the dissolution of gold by humic acids, other experiments were made utilizing humic acids which were purified by electrodialysis. With that exception, the conditions for the past and present experiments were the same. For the present experiments gold was subjected to 0.1 to 5.0 per cent unadulterated humic acid sols for periods ranging from one to thirty days. In addition, gold was exposed to humic acids to which had been added: (1) colloidal manganese dioxide and 3.0 per cent of concentrated hydrochloric acid, (2) pulverized manganese dioxide and potassium chloride, and (3) potassium chloride and potassium nitrate. The object of each of these three series of experiments was to determine whether nascent chlorine, if set free, would attack gold in the presence of humic acids. However, neither the purified humic acids alone nor those to which the above mentioned substances had been added, showed the slightest evidence of taking gold into solution.

Some time after these experiments were concluded, the writer discussed his investigations and those of Freise with Dr. Hernán Garcés of Medellín, Colombia. As a consequence, Dr. Garcés decided to carry out further experiments on gold using humic acids extracted from the lignitic coals (Tertiary) of the district around Angelapolis in the Department of Antioquia, Colombia, in the hope that these South American humic acids might have some of the solvent properties ascribed by Freise to those of the Carangola lignite of Brazil. However, the results obtained by Dr. Garcés, like those of the writer, were entirely negative.

The humic acids for all of the writer's experiments were extracted from peat taken from various bogs in the vicinity of Minneapolis and Saint Paul, Minnesota; and from lignite of the Fort Union formation (Tertiary) at the mines of the Lehigh Briquetting Company at Lehigh, N. Dakota.

DISCUSSION OF THE "SOLUBILITY" OF GOLD IN HUMIC ACIDS.

It is quite conceivable that in certain localities organic matter may play some part in the migration of gold. For example, prior to Freise, E. E. Lungwitz [7] linked the solution of gold with vegetation and its decomposition products, but did not attribute the solvent action to organic matter, though he considered its presence to be of first rank importance for its transportation. He stated that when nitric acid and sulphuric acid, which may be produced by the oxidation of vegetable matter, come together with sodium chloride in the presence of gold, gold chloride results. As gold chloride is reduced with great ease, he postulated a reaction of the gold chloride with some unknown vegetable-decomposition product such as the brown coloring matter of tropical streams. Thus, a gold-bearing molecular complex is formed in which the gold is more difficultly reduced and, hence, can be carried great distances.

[7] Lungwitz, E. E.: Der geologische Zusammenhang von Vegetation und Goldlagerstätten. Zeit. für praktische Geologie, pp. 71–74, 1900.

Obviously, this mode of solution and migration is quite different from that claimed by Freise who holds that elemental gold is converted to a gold humate by direct reaction with humic acids and without the aid of oxidizing agents.

As previously pointed out by the writer, any chemical reaction between humic acids and elemental gold must be regarded as oxidation; and it is difficult to understand how an element which tends to retain its valence electrons as tenaciously as gold does, could be oxidized by humic acids, a reducing agent.

Humic acid micells have a great affinity for water by virtue of which each of them is enveloped in an aqueous atmosphere which moves with, and is an integral part of, the micell. In the three phase system gold-water-humic acid there is no evidence that this atmosphere is either destroyed or penetrated by the gold; and that there is no contact between the gold and the humic acids proper, is strongly indicated by the fact that humic acids do not tend to adhere to the gold surface when it is withdrawn from the humic acid hydrosol, while the water does. Thus, if they do not touch, how can they react?

On the other hand, even if there should be contact, the amount of reacting surface of the effective part of the many molecule-species of which humic acids are comprised is infinitely less than what it would be if the solvent existed in molecular, atomic, or ionic dispersion; and the only conclusion that can be drawn is that the absolute action of that fraction of the molecules in Carangola lignite and Brazilian swamp water and streams which reacts with gold, must be extremely powerful to give the results obtained by Freise—apparently greater than that of cyanide.

Freise's assertion that he was able to dissolve gold by humic acids extracted from material which has advanced to the lignitic stage of coalification as well as by the humic acids of present-day streams, is either a remarkable coincidence or signifies a certain degree of universality for this property, suggesting that it should not be restricted to the humic acids of Brazil nor to those of any age. He does not say, but the Carangola lignite that he used, is most likely Tertiary. Those used in the experiments dealt with in this paper are also Tertiary.

In Freise's field experiments, a stream of water high in humus was made to sink in and pass through a 50-foot closed flume packed with clay, sands, and kaolin; and, with gold dust added in the upper one-tenth of the flume. He found, by taking samples at 15-foot intervals over periods ranging from ten to sixty days, that gold was transported by the stream. Freise concluded that the gold migrated chemically—as a humate.

It is difficult to understand what physical or chemical change could take place in the short distance of 15 feet to cause the precipitation of the dissolved gold. This is all the more striking in view of the fact that Freise states that, ". . . it is indispensable for the precipitation of gold that the gold humate in its underground circulation meet strongly mineralized waters such as carbonate or sulphate waters." For his experiments in which the migra-

tion of gold was most effective and rapid, the flume contained only "thoroughly washed sand"; and he makes no mention of introducing a precipitant.

That Dr. Freise did dissolve gold and even platinum by humic acids is now accredited by many geologists; but it seems there still remains much to be explained before this conclusion can be categorically accepted.

EXPERIMENTS WITH SILVER, COPPER, AND ZINC MINERALS IN HUMIC ACIDS AND TRUE ORGANIC ACIDS.

Three series of experiments, using 2.5 per cent sols of humic acids purified by electrodialysis, were made on each of the following minerals: Argentite, stephanite, proustite, pyragyrite, polybasite, chalcocite, covellite, chalcopyrite, enargite, bornite, malachite, azurite, cuprite, and sphalerite.

For the first series, the humic acids were extracted by precipitating with acetic acid; for the second, by hydrocloric acid; and for the third series, KNO_3 was added to the humic acids in order to determine whether the nitric acid liberated by hydrolytic adsorption would be of sufficient concentration to attack the minerals. Two different acids were used to precipitate the humic acids after their extraction in order to inquire into any possible effect that this might have on their reported ability to dissolve minerals.

Polished surfaces of the minerals were carefully studied and then placed in the humic acids and after the desired time elapsed they were re-examined for any changes that might have taken place. By this method even a slight degree of attack may be observed; however, after periods of 40 and 60 days in humic acids, the minerals showed no indications of etching or tarnish. The carbonates do not take a good polish; so, in addition to their polished surfaces, crystals of malachite having faces of high luster were also exposed to the humic acids; likewise, there was absolutely no evidence of attack.

From these experiments, it appears that neither humic acids nor the nitric acid they may liberate through hydrolytic adsorption by the presence of potassium nitrate, will attack any of the mentioned minerals.

In addition to the foregoing, the following tests were made: A strip of copper, weighing 18.1829 grams and having a total area of 40.6 cm.^{2}, was placed in a 2.0 per cent purified humic acid sol; and, after 30 days, was found to weigh 18.1759 grams—a loss of 0.1723 milligrams per cm.^{2} Another strip having an area of 71.3 cm.^{2} was found to have lost 10.5 milligrams, or 0.1475 milligrams per cm.^{2}, during the same time, in a 2.0 per cent humic acid sol to which potassium nitrate had been added.

Inasmuch as carbon dioxide is invariably associated with humic acids, it is pertinent to observe that, in air-saturated distilled water, the amount of copper dissolved that can be attributed to the presence of atmospheric carbon dioxide, corresponds closely to the amount of copper dissolved by the humic acid sols.[8]

Artificial cuprous oxide, cupric sulphide, and cuprous sulphide in powder form were treated with the following series of miscellaneous solvents at room temperature: one-tenth normal solutions of oxalic, citric, tartaric, lactic,

[8] Comey-Hahn, A Dictionary of Chemical Solubilities—Inorganic, Sec. Ed., p. 29, 1921.

formic, and acetic acids; saturated solutions of salicylic and benzoic acids;[9] distilled water; and peat extracts. The acids were dissolved in distilled water without removing the atmospheric gases. The peat extracts were obtained by digesting a large amount of peat in a small amount of water for several weeks and then filtering through muslin. An orange-yellow liquid was obtained; and found to be 0.0019 normal in respect to unknown acids.

Enough of each copper compound was weighed out to contain two grams of copper for each experiment. This was placed in 500 c.c. of each of the above-mentioned liquids.

After 40 days the liquids were prepared for analysis by completely destroying the organic acids; and, subsequently, removing the oxidizing agents used in their destruction. The liquids which dissolved large amounts of copper were analyzed by the iodide method. Those which dissolved smaller amounts were analyzed colorimetrically by converting to the blue cupric ammonia complex.

The amounts of copper in solution after 40 days are given in the following table:

Acids and Disassociation Constants $\times 10^{-4}$	Amount of Cu in solution in milligrams per 100 c.c. of solution after 40 days		
	Cu_2O	Cu_2S	CuS
Oxalic 380.00[10]	3.15	2.79	2.56
Salicylic 10.60	29.00	16.80	40.50
Tartaric 9.70	28.73	23.86	33.53
Citric 8.70	21.12	34.12	61.65
Formic 2.14	106.01	39.75	72.51
Lactic 1.38	378.35	31.80	57.61
Benzoic 0.67	25.95	23.15	27.82
Acetic 0.18	94.80	30.95	49.17
Peat Extract	2.08	2.08	1.48
Humid Acid Sol 1.0 per cent (supernatant liquid)		1.22	0.57
Distilled Water (blank)	0.63	1.87	1.39

[10] The relatively small amounts of copper dissolved in oxalic acid are due to the low solubility of copper oxalate.

Although the quantity of organic acids in metalliferous deposits is generally unimportant, the point is: true organic acids are effective solvents of copper oxide and copper sulphides, whereas the humic acids appear to be no more effective than the water in which they are dispersed.

EXPERIMENTS WITH IRON AND MANGANESE IN HUMIC ACIDS AND TRUE ORGANIC ACIDS.

Many investigations, both in the laboratory and in the field, have been made to determine the degree of solvent action of peat solutions on rocks and

[9] At 20° Centigrade, 1.8 grams of salicylic acid dissolve in one liter of solution, and 2.2 grams at 25°; 0.013 N. and 0.016 N., respectively. At 20°, 0.289 and 0.343 grams of benzoic acid dissolve per 100 c.c. of solution or to the extent of 0.0237 N. and 0.0281 N., respectively. Reference: Seidell: Solubilities of Inorganic and Organic Compounds, vol. 1, pp. 133 and 588, Sec. Ed.

especially on those minerals containing iron.[11] There have also been many statements concerning the power of humic acids to reduce and dissolve ferric iron. Lovering, in his report on iron and silica in peat extracts,[12] uses the terms "humic acids" and "peat solution" synonymously; but, as far as the writer is aware, no one studying the solubility of iron minerals actually isolated humic acids for this purpose.

During the present investigations, the polished surfaces of earthy hematite, specular hematite, magnetite, and cleavage pieces of siderite were exposed to 2.6 per cent humic acid sols. Of these minerals, only siderite was attacked. It was slightly but unmistakably etched after having been in contact with the humic acid sols for 110 days.

The following experiment was made to verify the lack of reaction between the polished surfaces of hematite and the humic acids. Enough 200-mesh artificial ferric oxide to give the equivalent of 2 grams of iron, was placed in 500 c.c. of 2.0 per cent humic acid sol which had been purified by electrodialysis. This was shaken daily and after 40 days the mixture was slightly acidified with hydrochloric acid in order to flocculate and settle the humic acids. Only a few drops were required. The resulting supernatant liquid was then decanted, filtered, and analyzed for iron. The time from acidification to filtration was 30 minutes. For purpose of control, an equal amount of ferric oxide was placed in another 500 c.c. of the same humic acids just before acidification and dealt with simultaneously by the same procedure. Likewise, 500 c.c. of humic acids, in which no ferric oxide had been placed, were flocculated by acidification; and the supernatant liquid analyzed for iron. The amounts of iron dissolved in parts per million of solution are shown in the following table:

IRON IN P.P.M. IN SUPERNATANT LIQUIDS

	Analyses in Duplicate	
Humic acids with Fe_2O_3, after 40 days	0.75	0.86
Humic acids with Fe_2O_3, after 30 minutes	0.63	0.65
Humic acids in which no Fe_2O_3 was placed	0.45	0.50

The amounts of iron that are indicated to have been dissolved are so minute as to show once again that the solvent power of humic acids is utterly unimportant and can be considered as nil. On the other hand, Harrar, using the same series of acids used by the writer in his experiments on copper oxide and sulphides and manganese dioxide, has conclusively shown that true organic acids can be effective solvents of iron oxides.[13]

As the genesis of sedimentary iron ores is much like that of manganese ores, the writer tested the solubility of manganese dioxide in eight of the or-

[11] Gruner, J. W.: ECON. GEOL., vol. 17, pp. 407–460, 1922; Lovering, T. S.: ECON. GEOL., vol. 18, pp. 523–540, 1923; Moore, E. S., and Maynard, J. E.: ECON. GEOL., vol. 24, pp. 272–303, 1929; Blanck, E.: Ernahr. Pflanze, vol. 29, pp. 41–43, 1933; and Chem. Erd., vol. 7; Mineraria, see Chem. Ab., p. 3426, 1931; et al.

[12] Lovering: op. cit., p. 526 and p. 532.

[13] Harrar, N. J.: Solvent effects of certain organic acids upon the oxides of iron. ECON. GEOL., vol. 24, pp. 50–61, 1929.

ganic acids which Harrar tried on limonite and on synthetic ferrous and ferric oxide.

In order to make the results of these experiments comparable to those of Harrar, enough artificial manganese dioxide was weighed out to give two grams of manganese for each test. This was placed in 500 milliliters of the various acids at a concentration of 0.1 normal. The tests were made at room temperature in air tight bottles. As a check, manganese dioxide was placed in distilled water containing atmospheric gases. The acids also contained atmospheric gases.

The results of these experiments, together with those of Harrar on iron oxides, are given in the following table:

Acids and Disassociation Constants $\times 10^{-4}$	Amount of Mn and Fe in solution in milligrams per 100 c.c. of solution after 40 days			
	MnO_2	Data by Harrar		
		FeO	Fe_2O_3	Limonite
Oxalic 380.00	15.6	42.525	97.463	6.646
Salicylic 10.60	29.3	14.627	4.891	21.568
Tartaric 9.70	156.5	14.022	3.175	10.528
Citric 8.70	121.8	31.122	2.961	16.159
Formic 2.14	104.3	5.792	0.951	4.329
Lactic 1.38	113.4	12.398	2.054	8.845
Benzoic 0.67	2.98	2.022	0.428	5.888
Acetic 0.18	1.55	0.520	0.327	0.505
Water (blank)	0.145			

The greater solubility of manganese dioxide in most of the organic acids in the foregoing table suggests that this may be a contributing factor effecting the more or less complete segregation of iron and manganese frequently found in bog ores.

The experiments on the solubility of manganese dioxide in true organic acids were supplemented by exposing polished surfaces of manganite, pyrolusite, braunite, hausmanite, psilomelane, and cleavage surfaces of rhodocrosite to 2.5 per cent humic acid sols for 40 days. None of the minerals exhibited evidence of attack or alteration, with the possible exception of rhodocrosite whose vitreous cleavage faces were almost imperceptibly dulled. There was considerable doubt whether this signified slight solvent action or was merely an exceedingly thin, alkaline film or water-insoluble deposit.

EXPERIMENTS ON CALCITE IN HUMIC ACIDS.

Cleavage pieces of icelandspar were exposed to purified humic acids and to humic acids to which had been added potassium nitrate. After 60 days, the cleavage faces that had been in contact with both of these exhibited evidence of attack. Approximately 50 per cent of the surface of the calcite, exposed to the purified humic acids alone, had been corroded to form microscopic triangular pits. The surface between the pits was also corroded, but

to a lesser degree. The total amount of attack, however, was no more than that to be expected from water carrying a little carbon dioxide.

The corrosion of the cleavage faces exposed to the humic acids to which had been added potassium nitrate, was more intense showing that acids liberated by exchange adsorption in accordance with the following formulas may, at least sometimes, act as mineral solvents:

$$\text{humic acid} + KNO_3 + nH_2O \rightarrow (\text{humic acid}, nH_2O, K)NO_3$$

$$(\text{humic acid}, nH_2O, K)NO_3 + H^+ + OH^- \rightleftarrows (\text{humic acid}, nH_2O, K)OH + HNO_3.$$

The brackets enclose the substances which are tightly held within the inner part of the electrical double layer of the humic acid micell; whereas the ions just outside of the brackets are loosely held in the outer part of the double layer. This loose adsorption bond makes it possible for hydroxyl ions to replace anions of salts to form free acids.

The calcite cleavage faces subjected to humic acids, to which potassium nitrate had been added, were 90 per cent covered by microscopic triangular pits.

CONCLUSIONS.

1. Observations made during these experiments show the humic acids to be lyophilic colloids which are insoluble in water and which, in themselves, impart no acidity to pure water.

2. These experiments do not substantiate reports that the humic acids dissolve minerals; on the contrary, the available evidence, both direct and indirect, tends to prove that they are not solvents.

3. The solvent action of aqueous humic acid sols was in no instance greater than that expected of water containing carbon dioxide in equilibrium with its atmospheric partial pressure.

4. The minute amounts of ferric oxide, siderite, and calcite, and the small quantities of synthetic copper sulphides dissolved in aqeous humic acid sols, appear to be due to accompanying impurities, mainly carbon dioxide, and to the water in which the humic acids were dispersed; and, not to the humic acids.

5. In these investigations there was no discernible difference in the chemical and physical properties of the humic acids from different places and of different geological ages.

6. Experiments on calcite indicate that free acid, liberated by the hydrolytic exchange adsorption of the anions of a neutral salt by humic acids, sometimes acts as a solvent for minerals.

7. Experiments with copper, manganese, and iron compounds show that the true organic acids are good solvents.

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TRANSPORT AND DEPOSITION OF THE NON-SULPHIDE VEIN MINERALS. I. INTRODUCTION.

F. GORDON SMITH.

ABSTRACT.

A summary is given of the experiments necessary before the alkali theory of vein formation can be said to be chemically possible or impossible. One question is the stability of the non-sulphide vein minerals in alkaline solutions at elevated temperatures. A method of transport of the vein-forming elements in alkaline solutions is postulated and will be tested by experiments.

There have been many general theories of vein formation and the chemistry of transport and deposition of the constituent minerals but at the present time there appears to be general agreement that veins are formed by deposition from aqueous solutions derived in some way from bodies of intrusive rocks. From that point on, two primary theories and two secondary theories have been built up. One theory holds that the solutions are acid, most of the metallic ions being simple, and the other, that the solutions are alkaline, most of the metallic ions being complex. A further possibility is that the vein-forming materials are carried in acid or alkaline solutions in colloidal form.

The transport and deposition of the metallic sulphides have received principal consideration in the discussion of the vein-forming mechanism, due to their very low solubility in neutral aqueous solutions, and Garrells (1944) has summarized quantitatively the experimental results obtained in recent years. It is evident that in neutral, dilute acidic and dilute alkaline solutions, the metallic sulphides have solubilities too low to be geologically important, but in strongly acidic and strongly alkaline solutions, especially at elevated temperatures, the solubilities are of the required order of magnitude. This leads to the following alternative mechanisms of transport: in true solution, the solutions being strongly acidic or alkaline *or* in colloidal solution, the solutions being weakly acidic, alkaline, or neutral. Now it is not difficult to point to natural examples of mineral deposits in veins showing physical forms which were probably due to coagulation of a colloid phase, but it is more difficult to imagine colloidal processes being responsible for all of the vein-forming processes, including differentiation from the source magma. It seems to be more reasonable to suppose that colloidal effects are subsidiary to the true solubility of minerals, and arise at the time of precipitation, or subsequent to the time of precipitation, of the minerals. This will be taken as assumed throughout the following discussion. Thus there remains the choice of acidic or alkaline solutions containing respectively enough free acid or alkali to allow the transport of the metallic components in true solution in the presence of sulphur also in true solution.

As Garrells (1944) has shown by quantitative calculations, the acid and alkali theories of sulphur mineral transport are mutually exclusive. Graton (1940) also has shown that it is geologically improbable that the two mechanisms of transport operate in sequence during vein deposition. The chemical proof of which of the two alternative theories is more nearly correct will depend upon a multitude of laboratory experiments which will eliminate one as being chemically impossible. That is, if conditions are set up duplicating the conditions postulated by one of the theories and under those conditions a family of minerals is unstable, then of course those conditions are not those which obtained during the deposition of those same minerals. Conversely, it can be shown that all of the families of minerals found in veins are stable under the conditions postulated by one of the theories, then that theory is chemically possible. It is not proved in the geological sense, but as long as it is chemically possible then it is geologically possible. It is hoped that the great variety of minerals found in veins with their diversity of stability limits will allow the testing of the various theories as they arise, and of these theories, one, and only one, will be found to fulfil the required stability criteria.

The theory currently being tested at the University of Toronto is the alkali sulphide theory which has been outlined in relation to gold ores (Smith, 1944). The following questions are among those which will have to be answered by experimental results before the possibility or otherwise of the alkali sulphide theory can be stated with any assurance:

(*1*) *Are all of the* (*a*) *simple sulphide,* (*b*) *double sulphide, and* (*c*) *sulpho-salt minerals stable in, and can they be crystallized from, alkaline solutions?*

The simple sulphides can be readily crystallized from alkaline solutions, including polysulphides such as *pyrite* (FeS_2) and subsulphides such as *realgar* (AsS) (Daubrée, 1879; Sénarmont, 1851; Becker, 1887; Ditte, 1907; Allen, Crenshaw and Merwin, 1912; Kania, 1936; Smith, 1939, 1940). Double sulphides such as *chalcopyrite* ($CuFeS_2$) have been formed in alkaline solutions (Sénarmont, 1851; Kania, 1936; Smith, 1939). Sulpho-salt minerals such as *proustite* ($3Ag_2S \cdot As_2S_3$) have been made in alkaline solutions (Sénarmont, 1851; Smith, 1939), but this is being studied more fully at the present time in this department by Mr. R. Béland with interesting results which will be published at a later date.

(*2*) *Can the* (*a*) *arsenides,* (*b*) *antimonides,* (*c*) *tellurides, and* (*d*) *metals be crystallized from alkaline solutions?*

There does not appear to be any record of metallic arsenides or antimonides having been synthesized in alkaline solutions. A representative telluride, *calaverite,* was recently synthesized in alkali sulphide solutions (Smith, 1943). Copper, silver, and gold have been crystallized from alkali sulphide solutions where the sulphur content is low (Smith, 1939, 1943; Lindner and Gruner, 1939).

(3) *Is the order of solubility of the metallic sulphides in alkaline solutions compatible with the observed order of deposition in nature?*

This question was partially covered in the recent paper on gold deposition (Smith, 1943), and fragmentary sequences have been shown to be similar to the natural sequence (Smith, 1939, 1940). Considerably more experiments on relative solubility of metallic sulphides, especially quantitative determinations, are desirable.

(4) *Is the solubility of the metallic sulphides in alkaline solutions great enough to explain their natural transportation?*

Very few quantative solubility measurements have been made due to the experimental difficulties. From the experiments carried out by the author it is evident that in alkaline solutions solubility of the sulphides is very much greater at elevated temperature than at room temperature, but the corrosive nature of the solutions and the high pressures make quantitative measurements very difficult indeed. The calculations made by Garrells (1944) indicate that in dilute alkali sulphide solutions the solubility of metallic sulphides is too low to be geologically important even up to moderately high temperatures. However, the solutions that concentrate the ore metals from the magma are not necessarily dilute and the temperatures may be considerably higher than those used in the calculations. Much more work will have to be done on this important branch of the problem.

(5) *Are all of the non-sulphide minerals stable in, and can they be crystallized from, alkaline solutions?*

Some of the non-sulphide minerals have been synthesized in alkaline solutions, notably *quartz* (Deville, 1862; Maschke, 1872; Friedel and Sarasin, 1879, and many others, as abstracted by Morey and Ingerson, 1937), *orthoclase* (Friedel and Sarasin, 1879, 1880, 1881; C. and G. Friedel, 1890; Bauer, 1911; Müller and Königsberger, 1912; Niggli, 1914; Schlaepfer and Niggli, 1914; J. W. Gruner, 1936), *albite* (Friedel and Sarasin, 1883), *muscovite* (Bauer, 1911; E. Gruner, 1929; Noll, 1932, 1936; O'Neill), *calcite* (Becquerel, 1852; Lemberg, 1883; Friedel, 1891; Bauer, 1911), *dolomite* (Sterry-Hunt, 1859), *chlorite* (Friedel and Grandjean, 1909), *barite* (Sénarmont, 1851), *fluorite* (Sénarmont, 1851). This problem is currently being studied in this department and the results will be published in the near future. We will attempt to synthesize the representative types of non-sulphide pegmatite and vein minerals in alkaline solutions, and if possible obtain some quanfitative solubility data.

(6) *Are the sulphide and non-sulphide minerals stable together and can they be crystallized simultaneously from alkaline solutions?*

This has yet to be demonstrated by experiment.

(7) *Can the observed wall rock alteration be duplicated by alkaline solutions?*

Some mineral alterations have been carried out in alkaline solutions by C. and G. Friedel (1890, 1891), Friedel and Grandjean (1909), E. Gruner

(1929), Lindner and Gruner (1939), and O'Neill, but there are a great many experiments still to be undertaken in this field. Problems involving change of soda to potash ratios and leaching or addition of alumina are important in many studies of ore genesis.

The data thus remaining to be gathered by experiment are the synthesizability of the arsenides and antimonides in alkaline solutions, the quantitative data of solubility of the metals in alkali sulphide solutions especially at elevated temperatures, the stability of the non-sulphide minerals especially in the presence of the sulphide minerals, and mineral changes in alkali sulphide solutions which parallel the natural wall rock alterations.

In the study of the non-sulphide pegmatite and vein minerals, the following minerals will be considered: *orthoclase* and *microcline* ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$), *quartz* ($SiO_2$), *albite* ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$), *corundum* ($Al_2O_3$), *muscovite* ($2H_2O \cdot K_2O \cdot 3Al_2O_3 \cdot 6SiO_2$), *apatite* ($Ca(F, Cl)_2 \cdot 9CaO \cdot 3P_2O_5$), *beryl* ($3BeO \cdot Al_2O_3 \cdot 6SiO_2$), *spodumene* ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$), *scheelite* ($CaO \cdot WO_3$), *zircon* ($ZrO_2 \cdot SiO_2$), *tourmaline* (a complex boro-silicate), *cassiterite* (SnO_2), *rutile* (TiO_2), *columbite* ($FeO \cdot Cb_2O_5$), *tantalite* ($FeO \cdot Ta_2O_5$), *wolframite* ($(Fe, Mn)O \cdot WO_3$), *monazite* ($Ce_2O_3 \cdot P_2O_5$), *magnetite* ($FeO \cdot Fe_2O_3$), *ilmenite* ($FeO \cdot TiO_2$), *titanite* ($CaO \cdot TiO_2 \cdot SiO_2$), *hematite* ($Fe_2O_3$), *barite* ($BaO \cdot SO_3$), *witherite* ($BaO \cdot CO_2$), *strontianite* ($SrO \cdot CO_2$), *fluorite* ($CaF_2$), *ankerite* ($CaO \cdot (Mg, Fe, Mn)O \cdot 2CO_2$), *dolomite* ($CaO \cdot MgO \cdot 2CO_2$), *calcite* ($CaO \cdot CO_2$), *anhydrite* ($CaO \cdot SO_3$), *gypsum* ($CaO \cdot SO_3 \cdot 2H_2O$). Taking the principal elements in the above minerals and arranging them in order of their basicity, the following result is obtained:

TABLE 1.

COMMONER ELEMENTS THAT FORM NON-SULPHIDE PEGMATITE AND VEIN MINERALS.

K Na Li Ba Sr Ca Mg	Be Fe^{3+} Mn Ce Fe^{3+} Al Zr Ti Sn Ta Cb W	P Si C B	S F Cl
basic oxides	amphoteric oxides (more basic) (more acidic)	acidic oxides	
(carried as simple ions in alkaline solutions)	(carried as complex oxy-ions in alkaline solutions)		(carried as simple ions in alkaline solutions)
(carried as simple ions in acid solutions)		(carried as complex oxy-ions in acid solutions)	(carried as simple ions in acid solutions)

In the previously mentioned paper on the application of the alkali sulphide theory to gold deposition (Smith, 1943), it was postulated that the rest-magma at the time of pegmatite formation is hot, aqueous, and alkaline. Con-

sidering a granitic magma, the solutions at the pegmatite stage would be saturated with quartz and feldspars and any further cooling would precipitate both, but the solutions would not yet be saturated with rarer compounds, such as those of phosphorus and lithium. It is now being postulated that the solutions are strongly enough alkaline so that the elements of Table 1 that can form complex oxy-ions would be carried as such, associated with simple ions such as those of sodium and potassium. That is, for example, boron, phosphorus, tantalum, zirconium, cerium, and beryllium would be carried as alkali borates, phosphates, tantalates, zirconates, cerates, and berylliates. As postulated previously, the heavy metals would be carried as complex thio-ions, *e.g.*, copper as an alkali thio-cuprite. As described above, the solutions would be strongly alkaline, but there is at least one important reaction that normally would proceed in such a way that the solutions would become less alkaline. This is the complex reaction involving sulphur and water (Allen's reaction). Normally the solutions would have to hold much sulphur in the polysulphide form (since polysulphides such as pyrite are formed), and this would be in equilibrium with hydrogen sulphide, sulphide ion, hydrosulphide ion, and sulphate ion. The action of the sulphide solutions on wall-rocks includes sulphidization. This loss of sulphide would be accompanied by an increase in the sulphate ion concentration. The loss of a weak acidic ion accompanied by the gain of a strong acidic ion would lower the alkalinity. If the ratio of sulphur to alkalis is high enough, the solution might even become acid, but before this condition is reached, a large part of the mineral load would have been dropped. Other wall rock alterations leading to decreased alkalinity would be albitization and sericitization.

We are now postulating that the pegmatite solutions are hot, aqueous, alkaline, and become cooler and less alkaline as they react with the vein walls during ascent from the magma. On this basis, as the solutions cool, in addition to the solubility of compounds such as lithium alumino-silicate being reached, the more basic amphoteric oxides would change progressively from the complex oxy-ion condition to that of the simple ion, and at that point, if an insoluble combination with acidic ions exists, that combination would precipitate. Also, if the basic oxide is insoluble in the solution, it would precipitate at the time it changes from the complex ion condition. Thus there would be at least three processes of mineral precipitation as the solutions cool and become less alkaline.

The first minerals which would be expected to precipitate would be those whose solubility limit is reached due to cooling as the solutions leave the magma but before there is extensive chemical reaction with the wall-rocks. These would be the more insoluble combinations of simple positive ions with complex negative oxy-ions or with simple negative ions. Somewhat later, the more basic amphoteric oxides would change from negative oxy-ions to positive simple ions, and either precipitate after combining with one or more remaining combinations of simple positive ions and negative oxy-ions or as simple oxides. Much later, the more soluble combinations of simple positive ions and negative oxy-ions or simple ions would precipitate.

Applying the above concept to the elements shown in Table 1, the generally

recognized sequence of deposition of the non-sulphide vein minerals is at once apparent. The first pegmatite minerals, *quartz* and *feldspars,* precipitate in abundance soon after the solutions leave the magma, lowering the silica content and probably removing most of the alumina. If other metallic ions are present that form alumino-silicates more insoluble than those of potash and soda, they would use up some of the alumina, *e.g., spodumene* and *beryl.* The elements remaining after this initial cooling stage thus would be:

$$\text{K Na Ba Sr Ca Mg} \;\Big|\; \text{Fe}^{2+}\ \text{Mn Ce Fe}^{3+}\ \text{Zr Ti Sn Ta Cb W} \;\Big|\; \text{P Si C B} \begin{matrix} \text{S} \\ \text{S} \end{matrix} \text{F Cl.}$$

The second stage could be considered to be that in which solubility limits of the rarer and somewhat less insoluble combinations are reached by cooling, and also that in which a decrease in alkalinity allows the conversion of some of the more basic oxy-ions to simple ions. Calcium phosphate and other relatively insoluble phosphates, such as *apatite, amblygonite,* and *monazite,* would appear, also borosilicates such as *tourmaline.* Ferrous and manganous combinations with titanate, ferrate, tantalate, columbate and tungstate ions would precipitate as *ilmenite, magnetite, tantalite, columbite,* and *wolframite.* Somewhat later, as the zirconate, titanate and stannate ions break down, *baddelyite, rutile* and *cassiterite* would precipitate. Since the solutions were saturated with silica before this stage, quartz would be precipitated throughout the sequence. The principal elements remaining after this second stage thus would be:

$$\text{Na K Ba Sr Ca Mg} \;\Big|\; \text{Si C B} \begin{matrix} \text{S} \\ \text{S} \end{matrix} \text{F Cl.}$$

The third stage could be considered to be that during which the simple positive ions precipitate with less and less insoluble combinations with the negative oxy-ions. Thus the barium ion would combine with the sulphate ion to precipitate *barite,* and in an analogous manner would be precipitated *witherite, celestite, strontianite, calcite, dolomite, fluorite, anhydrite,* and *gypsum. Quartz* would continue to precipitate throughout this stage. The elements remaining after stage three would be:

$$\text{K Na} \;\Big|\; \text{Si C B} \begin{matrix} \text{S} \\ \text{S} \end{matrix} \text{Cl.}$$

The solutions would then mingle with ground water or flow on the surface as alkaline hot springs.

A series of experiments is now in progress, testing the above postulate with regard to the stability or otherwise of the representative minerals in alkaline solutions, and the results will be published as they are obtained.

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Toronto, Canada,
Nov. 22, 1945.

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A PORTABLE DIFFERENTIAL THERMAL ANALYSIS UNIT FOR BAUXITE EXPLORATION.

STERLING B. HENDRICKS, SAMUEL S. GOLDICH, AND REUBEN A. NELSON.

ABSTRACT.

A small differential thermal analysis unit that embodies the fundamental features of larger laboratory models is designed for field exploration for bauxite and related materials. The apparatus, requiring only a source of electrical power, combines portability with ease of operation and rapid analysis. The portable unit is suitable for quantitative work and has been successfully applied in bauxite exploration on the island of Hispaniola.

INTRODUCTION.

THE identification of bauxite in the field on the basis of physical characteristics is often uncertain, because aluminous lateritic materials exhibit a variety of forms some of which closely resemble earthy and concretionary substances that are wholly unsuitable for use as aluminum ore. Preliminary mineralogical information needed at once for the efficient prosecution of field studies can be conveniently supplied by differential thermal analysis. A portable unit designed and built in the laboratory of the Bureau of Plant Industry, Soils, and Agricultural Engineering of the U. S. Department of Agriculture was used by a field party of the Geological Survey of the U. S. Department of the Interior in exploration for bauxite on the island of Hispaniola.[1] This unit was useful not only in identifying gibbsite, boehmite, and other minerals, but also in estimating the chemical composition or grade of the material. The portability of the apparatus, the convenience and ease of operation, and the notable saving of time effected over routine chemical analysis are features that are particularly valuable to geologists and mining engineers engaged in exploration for bauxite or other materials to which the apparatus is applicable.

PRINCIPLE OF DIFFERENTIAL THERMAL ANALYSIS AND DESIGN OF PORTABLE UNIT.

Reactions taking place in minerals on heating such as the loss of water or of carbon dioxide lead to the absorption of heat; whereas the crystallization of amorphous materials or the burning of organic matter results in evolution of heat. If the mineral is heated rapidly, the temperature range in which reactions take place and the heat change involved can be used both for the identification of the mineral and for the estimation of its relative abundance. A convenient method for measuring these properties is differential thermal

[1] Cooperative investigations with the governments of the Republic of Haiti and the Dominican Republic sponsored by the United States Department of State.

analysis which was first used by Le Chatelier [2] in 1887 and which has been used extensively in recent years in the study of clays.[3] Le Chatelier's method depends upon measuring the difference in temperature between the mineral being examined and an inert substance as the two are heated rapidly. This is accomplished by having one junction of a thermocouple in the powdered mineral and the other junction in the inert substance. A separate thermo-

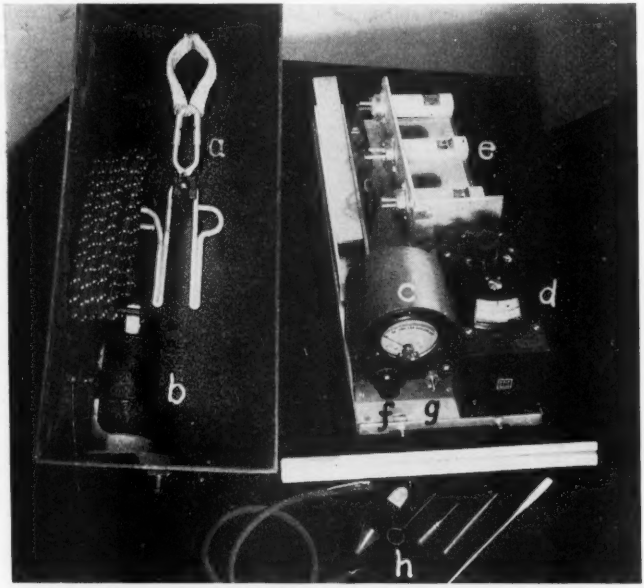

FIG. 1. Portable differential thermal analysis unit with various parts indicated: a, tongs for handling furnace; b, furnace in carrying position in lid of set; c, milliammeter for indicating sample temperature; d, galvanometer for indicating differential temperature; e, sample blocks; f, selector switch; g, sensitivity switch; h, accessories.

couple is used to determine the temperature of the samples. The response of a galvanometer connected to the thermocouples can be read directly or recorded photographically, the latter method generally being used in laboratory units.

A portable unit for carrying out differential thermal analysis is shown in Fig. 1. The instrument complete with accessories weighs about 20 pounds and can be carried easily by the handle grip. It can be set up for operation

[2] Le Chatelier, H., Zeit. Phys. Chem. 1: 396, 1887. Bull. Soc. franc. min., 1887, 204.

[3] Hendricks, S. B. and Alexander, L. T., Soil Science 48: 257 (1939). Grim, R. E. and Rowland, R. A., Amer. Mineral. 27: 746, 801 (1942). Speil, S., Berkelhamer, L. H., Pask, J. A. and Davis, B., "Differential Thermal Analysis," Technical Paper 664, U. S. Bureau of Mines (1945).

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within a few minutes and requires only a source of electrical power which may be either alternating or direct current of about 110 volts. The apparatus has three nickel sample blocks. Chromel-alumel thermocouples are used as indicated in the wiring diagram (Fig. 2). These are of large diameter (0.025 in.) wire to insure long life and durability. Temperatures of the samples are obtained from deflections of a Weston model 301 milliammeter with an internal resistance of about 60 ohms. Differences in temperature between the test sample and the inert substance (Al_2O_3) are measured on a Leeds and Northrop rugged portable galvanometer with a coil resistance of about 12 ohms. The galvanometer can be connected with a series resistance, reducing its sensitivity when large temperature differences are developed in the heated sample.

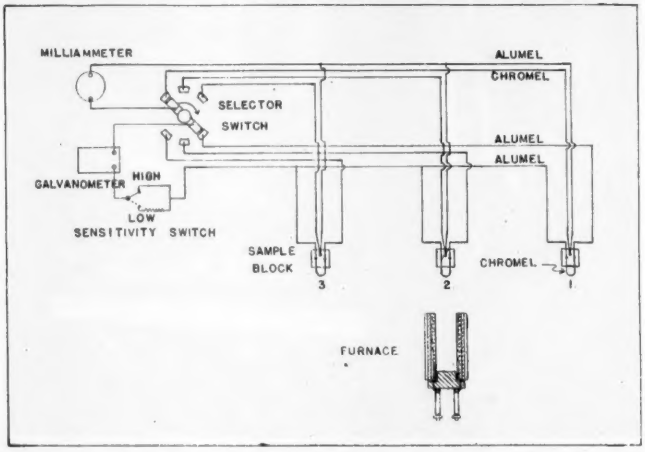

FIG. 2. Wiring diagram for the portable differential thermal analysis unit.

The heating unit is of the standard 500-watt cylindrical type. An insulating disc on which the hot furnace can be rested and a pair of tongs are provided. These, together with the heating unit, can be fastened in the lid of the apparatus. Other accessories for transferring the sample to the block and for removing it after completion of the analysis are carried in a small box attached to the base of the instrument.

Although the principle of operation of the portable unit is fundamentally the same as that of laboratory types, certain arrangements were made to facilitate rapid work with bauxite samples. The analysis is started with the furnace at maximum temperature rather than at room temperature, and successive runs can be made with the three crucibles. The curves representing the analyses are obtained by plotting galvanometer readings indicating differential temperature (ordinate) against temperature readings from the milliammeter (abscissa). The complete operation from the loading of the three

crucibles to the plotting of the final results can be done in one hour. An approximate knowledge of the gibbsite content of a sample can be had in about five minutes simply by noting the maximum deflection of the galvanometer in the temperature range of gibbsite decomposition.

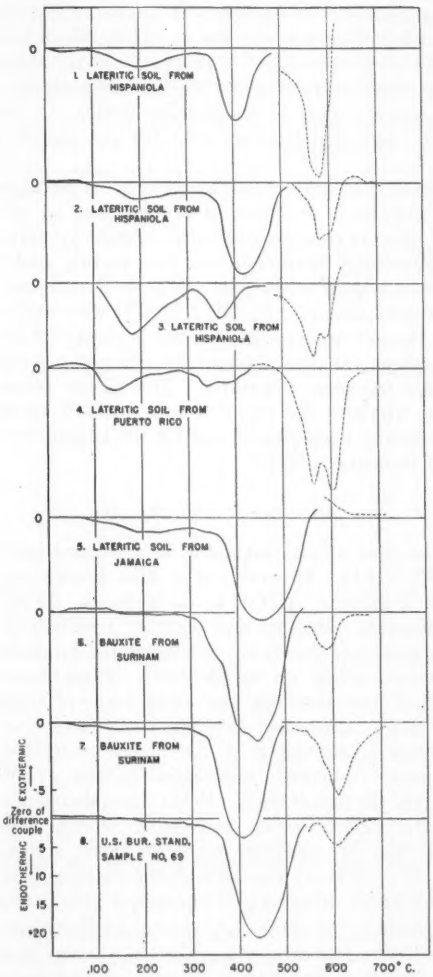

FIG. 3. Differential thermal curves representing samples of lateritic soil and of bauxite from analyses made with the portable unit. Solid curves at low sensitivity, dotted curves at high sensitivity on the galvanometer.

Emphasis has been placed on simplicity of construction and durability. Three sample blocks afford a reserve against breakdown in remote localities. Heating curves can be constructed for each of the sample blocks, and in the event of irreparable damage to the milliammeter, approximate temperatures may be determined by time readings. For quantitative work it is necessary to calibrate the apparatus with samples of known composition. Because of individual characteristics, each crucible or sample block should be calibrated separately. The results presented in this paper were obtained using a single crucible. Close checks were obtained in duplicate analyses made in the other crucibles. All samples must be handled identically. A small beam balance or spring balance calibrated to weigh a 0.3–0.4 gm. sample can be carried for field work.

The characteristics of differential thermal curves are dependent on the rate of heating, the amount of the mineral present, and on other factors. This must be kept in mind in comparing results obtained by different investigators. Some typical differential thermal curves representing analyses of samples of lateritic soil and of bauxite made with the portable unit are shown in Fig. 3. For comparison three samples (Nos. 1, 2, and 3) were analyzed in the recording differential thermal analysis unit of the Bureau of Plant Industry (Fig. 4). The endothermic peaks on the portable unit come at higher temperatures than on the large recording apparatus. This is the result of the different rates of heating, which in the portable unit varies from 90° to 60° C. per minute with increasing temperature, and for the laboratory instrument of the Bureau of Plant Industry is 12° C.

MINERALOGY OF BAUXITE.

Bauxite at one time was considered to be a mineral species with the composition of $Al_2O_3.2H_2O$. However, it is now known that material called bauxite consists of gibbsite, $Al(OH)_3$, or boehmite, $AlO(OH)$, or of mixtures of these minerals. Bauxite also contains a variety of characteristic or typical minerals which are genetically related to the processes of lateritization or to later processes acting on the deposits. These minerals include clay minerals; oxides of iron, titanium, and manganese; phosphates of aluminum and possibly of iron; carbonates; sulphides; and others. A third group of minerals in bauxite is derived from the parent materials from which the bauxite was formed. Commonly these minerals represent the more resistant or stable minerals of the parent rock. Relict minerals include quartz, ilmenite, magnetite, titanite, rutile, zircon, and many others. These minerals, in amounts of less than five percent, might be called accessory minerals; in larger amounts, they are better classed with the characteristic minerals.

Qualifying adjectives indicating the principal characteristic mineral may be used as composition indicators, *i.e.*, clayey, kaolinitic, ferruginous, hematitic, limonitic, sideritic, quartzose, etc. The terminology is no more uncertain than is that of sedimentary materials in general. Uncertainty arises, however, if the mineralogical composition of the bauxite in question is not known. The name bauxite is retained for field use similar to the present usage of limonite

which is known to be composed largely of the mineral goethite. The essential minerals and some of the characteristic minerals and their behavior in the portable differential thermal analysis unit are briefly discussed.

ESSENTIAL MINERALS.

Gibbsite.—Gibbsite, $Al(OH)_3$, is the principal mineral of bauxite or aluminous laterite formed by the weathering of igneous rocks or other aluminous materials. A strong endothermic reaction is obtained on loss of water

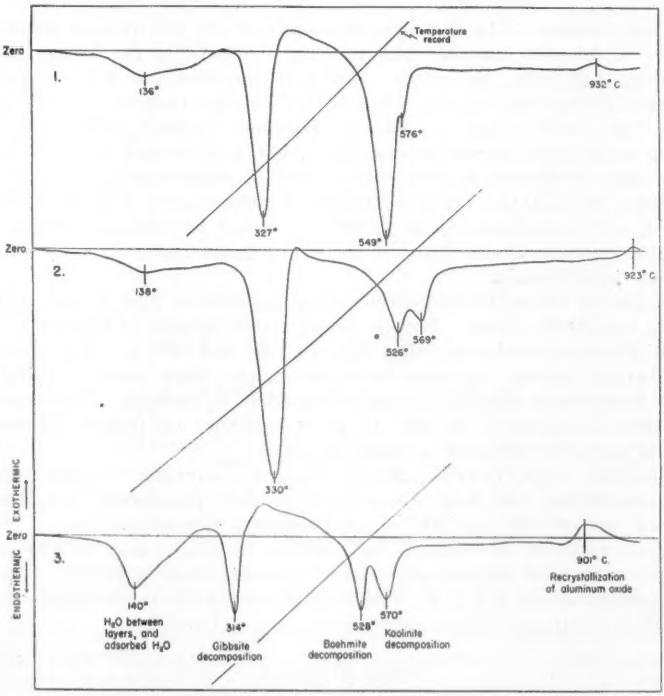

FIG. 4. Differential thermal curves representing samples of lateritic soil from Hispaniola made with the recording apparatus of the Bureau of Plant Industry.

from gibbsite. Samples of relatively pure gibbsite give endothermic peaks between 420° and 450° C. on the portable unit.

Boehmite.—Boehmite, AlO (OH), is the chief mineral in many of the bauxite deposits in the limestones of the Mediterranean region and occurs in the lateritic soils on Tertiary limestones in the West Indies islands. Boehmite

was long the mystery mineral of bauxite. It remained for De Lapparent [4] in 1927 to establish the mineral identity of boehmite, and this discovery led to the discrediting of bauxite as a mineral species. Boehmite shows a strong endothermic reaction between 500° and 600° C. A sample of boehmitic bauxite from Var, France, shows an endothermic peak at 576° C.

Amorphous Material.—Various names such as cliachite have been applied to the so-called "amorphous" material in bauxite. Further study of the fine-grained material is necessary before its exact nature can be stated.

CHARACTERISTIC MINERALS.

Clay Minerals.—The clay minerals associated with the hydrous aluminum oxides in lateritic materials generally are members of the kaolin group. Kaolinite, halloysite, and endellite have been identified, but it is not always practical to determine the clay minerals, and for most purposes the identification of the kaolin group is sufficient. Kaolinite, $Al_2Si_2O_5(OH)_4$, shows a strong endothermic reaction between 550° and 650° C. caused by loss of water and a sharp exothermic reaction at about 980° C. which is probably due to the formation of γ–Al_2O_3. Well-crystallized kaolinite gives a peak at about 636° C. The exothermic peak at 980° C. cannot be obtained, because the portable apparatus is not designed for temperatures above 700° C. without use of a special furnace.

Halloysite differs in composition from kaolinite in that it may contain excess (absorbed) water. Because of this water, samples of halloysite commonly show an endothermic effect between 100° and 200° C. The principal endothermic reaction for many halloysite samples takes place at a slightly lower temperature than the corresponding effect in kaolinite. The exothermic effect is developed at 980° C. as in kaolinite. A typical differential thermal curve for halloysite is shown in Fig. 5.

Endellite, $Al_2Si_2O_5(OH)_4.2H_2O$,[5] changes irreversibly to halloysite at low temperatures with loss of water and shows a pronounced endothermic reaction between 100° and 200° C. on differential thermal analysis.

Montmorillonite and related clay minerals, nontronite and beidellite may be present in some lateritic materials. A thermal analysis record of montmorillonite is shown in Fig. 4. The endothermic reaction in the neighborhood of 200° C. is strongly dependent upon the relative humidity.

OTHER MINERALS.

Diaspore has been reported in bauxites but is not a common mineral in normal deposits. Diaspore shows an endothermic reaction in the same temperature range as boehmite and kaolinite. A sample from Missouri developed an endothermic peak at 590° C. (Fig. 5).

Goethite is not as common in bauxite or laterite as hematite. In some deposits goethite is a secondary mineral formed at the expense of hematite.

[4] De Lapparent, J. L., Compt. Rend. Acad. Sci. Paris 184: 1661 (1927).

[5] Alexander, L. T., Faust, G. T., Hendricks, S. B., Insley, H., and McMurdie, H. F., Amer. Mineral. 28: 1 (1943).

Goethite shows an endothermic reaction that can interfere with the determination of gibbsite. A sample of goethite developed an endothermic peak at a temperature of 420° that is equivalent to the reaction of about 20 percent of gibbsite (Fig. 5). This amount of gibbsite, however, would develop an endothermic peak at about 370° C.

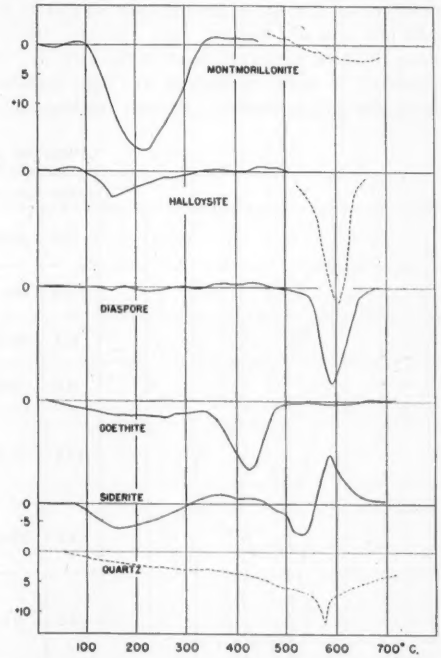

FIG. 5. Differential thermal curves for some characteristic minerals of lateritic materials. Dotted curves at high sensitivity on the galvanometer.

Siderite occurs in some deposits that have been subjected to reducing ground water conditions. Siderite gives an endothermic reaction with loss of carbon dioxide and an exothermic reaction associated with the oxidation of the ferrous iron (Fig. 5). The exothermic reaction is typical and can be used for the identification of siderite in the absence of sulphides and organic matter.

Quartz gives a sharp endothermic reaction at about 575° C. caused by the inversion from the low to the high form (Fig. 5). If finely divided quartz is suspected in considerable amounts, it may be detected by allowing the crucible with the sample to cool and then repeating the determination. The reversible alpha-beta inversion will be repeated without interference from hydrated minerals which will have been decomposed in the initial run.

CALIBRATION OF PORTABLE UNIT.

The multiple-crucible unit was calibrated and used in Washington, D. C., in the laboratory study of samples collected in Hispaniola. A series of samples was prepared by mixing a representative sample of the aluminous lateritic soil from Hispaniola with kaolinite in different proportions. The differential thermal curves for these samples are shown in Fig. 6. Samples with more than 50 per cent of kaolinite were run at "low sensitivity" of the galvanometer, using the accessory resistance in the circuit. These determinations may be converted to units equivalent to "high sensitivity" determinations by multiplying the galvanometer deflection readings by a factor of 3.

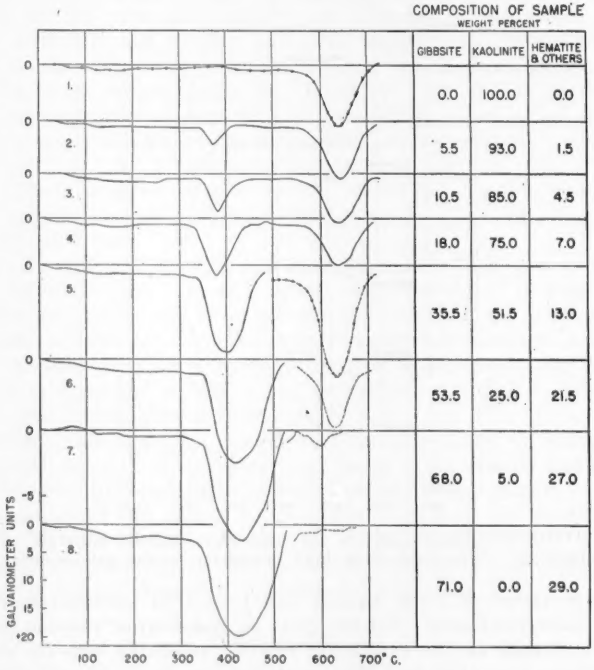

FIG. 6. Differential thermal curves for calibration of the portable unit. Dotted curves at high sensitivity on the galvanometer.

QUANTITATIVE ANALYSIS.

Gibbsite-Kaolinite.—Two methods may be used for the quantitative determination of gibbsite and kaolinite. The more reliable one involves determining the area under a line drawn across the parts of the differential thermal curves representing the endothermic reactions for gibbsite and for

kaolinite. Planimeter measurements of the calibration records (Fig. 6) are the basis for the curves shown in Fig. 7 for estimating gibbsite and kaolinite. In most samples gibbsite can be determined with an accuracy of about 10 per cent of the amount present. Greater accuracy is possible, but for the purposes that the portable unit will be called on to serve, further refinement does not appear necessary. In the field fairly accurate area measurements can be obtained by counting the squares of the graph paper used in plotting the curves.

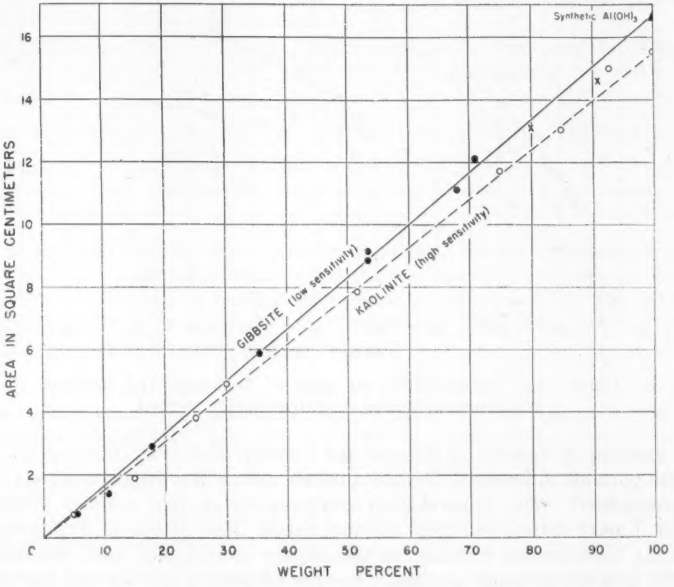

FIG. 7. Curves for the quantitative determination of gibbsite, and kaolinite by area measurement method.

A second method for estimating gibbsite and kaolinite content is illustrated in Fig. 8. The amplitude of the parts of the curve representing the endothermic reactions of gibbsite and of kaolinite may be used to estimate the relative amounts of these minerals. This method is not reliable for gibbsite in amounts exceeding 30 per cent. The results plotted in Fig. 8 were obtained under controlled laboratory conditions, and it is not likely that they are reproducible under most working conditions. However, for rapid work the method is advantageous.

Boehmite.—Lateritic materials containing boehmite present a special problem since the endothermic reaction for kaolin occurs at only slightly higher temperature than that for boehmite when both minerals are present the reactions may interfere to a certain extent. It should be noted that boehmite does

not interfere with gibbsite. If boehmite and kaolinite are present in about equal amounts, they may show distinct endothermic peaks (analyses 2, 3 and 4, Fig. 3). If either is in marked excess, this mineral may be identified by the temperature at which the endothermic peak is developed. An estimate of one or of both of these minerals may be made using the curves of Fig. 8.

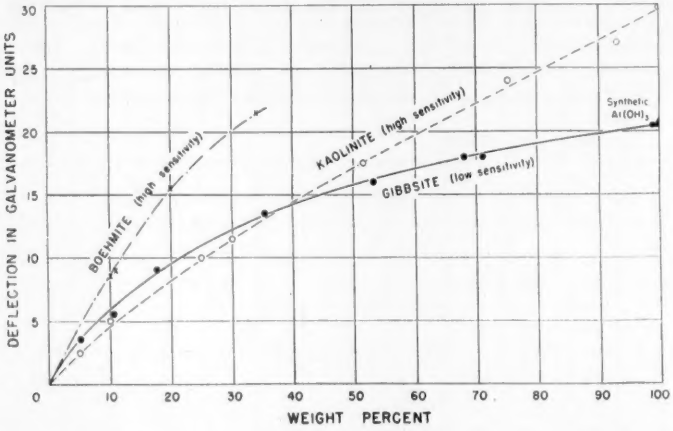

FIG. 8. Curves for the estimation of gibbsite, boehmite, and kaolinite by the maximum deflection of galvanometer method.

Analyses of Samples of Bauxite and Lateritic Soil.—To illustrate the use of the portable differential thermal analysis unit, a few typical analyses may be considered. The mineralogical compositions of five samples given in Table 1 were determined from thermal curves, four of which are shown in Fig. 3. Gibbsite and kaolinite, in the absence of boehmite, were determined by the area measurement method. For the samples of lateritic soil, boehmite and kaolinite were determined from the amplitude of the parts of the curves

TABLE 1.

MINERALOGICAL COMPOSITION OF BAUXITE AND LATERITIC SOIL SAMPLES ESTIMATED FROM DIFFERENTIAL THERMAL CURVES.

Sample	Weight, per cent			
	Gibbsite	Boehmite	Kaolinite	Others
Bureau of Standards bauxite sample No. 69 (No. 8, Fig. 2)	79	—	7	14
Bauxite from Surinam (No. 6, Fig. 2)	87	—	9	4
Bauxite from Surinam (No. 7, Fig. 2)	62	—	27	11
Lateritic soil from Hispaniola (No. 2, Fig. 2)	40	10	17	33
Lateritic soil from Hispaniola	25	17	27	31

representing the endothermic effects of these minerals. It may be noted that differential thermal curves such as No. 1 and No. 3 in Fig. 3 permit the determination of gibbsite and the approximation of boehmite but not of kaolinite. No discernible break for kaolinite was obtained in sample No. 1, and No. 3 the reaction is incompletely developed. This is probably due to the exothermic reactions indicated in the curves which may be caused by a small amount of organic matter in these soil samples.

The contents of alumina, silica, and water may be calculated from the mineralogical composition by use of the theoretical compositions for gibbsite, boehmite, and kaolinite which follow:

Mineral	Composition	Weight per cent		
		H_2O	Al_2O_3	SiO_2
Gibbsite	$Al(OH)_3$	34.6	65.4	
Boehmite	$AlO(OH)$	15.0	85.0	
Kaolinite	$Al_2Si_2O_5(OH)_4$	14.0	39.5	46.5

The calculated alumina, silica, and water contents for the five samples and the values for these constituents obtained from chemical analyses are given in Table 2. The loss on ignition determined on samples of lateritic soil usually represents some absorbed water; hence the determined value is generally greater than the calculated one.

TABLE 2.

CALCULATED AND DETERMINED PERCENTAGES FOR Al_2O_3, SiO_2, AND LOSS ON IGNITION.

Sample	Weight, per cent			
		Al_2O_3	SiO_2	Loss on ign.
Bureau of Standards bauxite sample No. 69	Calculated	54.5	3.3	28.4
	Determined	55.1	6.3	28.8
Bauxite from Surinam, No. 6	Calculated	60.5	4.2	31.4
	Determined	62.4	3.7	31.7
Bauxite from Surinam, No. 7	Calculated	51.3	12.6	25.2
	Determined	49.9	13.2	24.2
Lateritic soil from Hispaniola, No. 2	Calculated	41.4	7.9	17.8
	Determined	44.5	8.5	20.2
Lateritic soil from Hispaniola	Calculated	41.5	12.6	15.1
	Determined	43.5	9.8	18.0

USE OF THE PORTABLE DIFFERENTIAL THERMAL ANALYSIS UNIT IN HISPANIOLA EXPLORATION.

A preliminary model of the portable differential thermal analysis unit figured in this paper was used in an investigation of aluminous lateritic soils as potential aluminum ore in the Republic of Haiti and the Domican Republic.

Representative samples of the lateritic material were sent by air-mail to the chemical laboratory of the Geological Survey in Washington, D. C., and the analyses were returned by cablegram. These samples were then used as standards, and other samples were compared and graded on a relative basis to guide the field exploration. Chemical data subsequently obtained for samples were in close accord with the conclusions relative to grade reached in the field by use of the portable unit.

ACKNOWLEDGMENTS.

Mr. Harlan R. Bergquist of the U. S. Geological Survey assisted in the field exploration in Hispaniola. Mr. Josiah Bridge and Mr. C. S. Ross of the Geological Survey read the manuscript. Their interest in the development of the portable unit and in its application to field exploration is appreciated. Miss Elizabeth C. Fischer of the Geological Survey assisted in the preparation of the Figures.

BUREAU OF PLANT INDUSTRY, SOILS AND AGRICULTURAL ENGINEERING,
U. S. DEPT. OF AGRICULTURE, BELTSVILLE, MD.,
U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Nov. 15, 1945.

DISCUSSION AND COMMUNICATIONS

SOME APPLICATIONS OF STRUCTURAL GEOLOGY TO MINING IN THE PACHUCA–REAL DEL MONTE AREA, PACHUCA SILVER DISTRICT, MEXICO.[1]

Sir: Having studied the geology of the Pachuca district for ten years (1926–1936) and published extensively on it,[2, 3, 4] comment by me on Mr. Thornburg's paper is to be expected, especially since I find it to contain misinterpretations of my published ideas on Pachuca, and conceptions of structural geology fundamentally different from mine. Since my publications are scattered in the literature and written in an involved and labored style, a brief recapitulation here may aid this discussion.

Geology of the Pachuca District. The Pachuca silver district consists of two contiguous subdistricts, Real del Monte on the east, Pachuca on the west, covering the southeastern half of the Sierra de Pachuca, a volcanic pile. The entire Sierra, but especially its southeast half, was intensely fractured and faulted before and during the period of silver mineralization (footnote 2, Fig. 2). The earliest diastrophism produced a great system of faults and fractures striking east-west, north of west, and south of west, with a linked pattern in places. The main movements on these faults were up or down the dip (footnote 2, p. 481). Many dikes intruded along fractures of this set, at the time the set was developing.

The master fault of this older system is the Vizcaina, crossing the center of the district in a direction north of west. It is a pivotal fault. In Real del Monte, where the Vizcaina dips south, the south block "went down" several hundred meters in relation to the north block. In the Pachuca area proper at the west edge of the district, the Vizcaina stands about vertically, but in places dips steeply north, in others steeply south (footnote 2, p. 454). In this area the north block "went down" several hundred meters in relation to the south block. Midway between Real del Monte and Pachuca displacement on the Vizcaina is zero, so that the faulting is pivotal or rotational.

Digressing for a moment, this pivotal fault, probably connected with crustal warping, exhibits the danger in the use of the term "normal fault" as a genetic instead of geometric definition, and with the implication that the hanging wall has actually dropped in response to gravity. Mr. Thornburg uses the term in that sense throughout his paper, as on page 283: ". . .

[1] Thornburg, C. L.: ECONOMIC GEOLOGY, XL, 4 (June–July 1945), 283–297.

[2] Wisser, Edward: Formation of the north-south fractures of the Real del Monte area, Pachuca silver district, Mexico. Transactions A. I. M. E., vol. 126 (1937), 442–486.

[3] Wisser, Edward: The Pachuca silver district, Mexico. Chapter in "Ore deposits as related to structural features." Princeton University Press, 1942, 229–235.

[4] Wisser, Edward: Discussion of paper by H. E. McKinstry: Structural control of ore deposition in fissure veins. Transactions A. I. M. E., vol. 144 (1941), 90–92.

'normal fault rupture' is the term used in referring to the type of fracturing that takes place in the process of normal faulting or the settling of earth blocks due to gravitational force." At Real del Monte the Vizcaina is a "normal fault" (I refer to the early, major displacement on it), although by my interpretation the footwall actually moved up in space while the hangingwall remained stationary (footnote 2, Fig. 5). At Pachuca the Vizcaina is a "normal fault" where it dips north, but nearby, where it dips south, it is a "reverse fault." Fortunately the "normal fault" solecism is on its way out; its survival with Messrs. Thornburg and Mead will be further discussed below.

Nothing in this older fracture system suggests formation by horizontal shear. On the contrary, I assign the system to readjustments in the cover of a growing and consolidating intrusive mass. Heterogeneous upward shove of the consolidating mass ruptured its cover, and pushed upward differentially the blocks between the ruptures. The cover was warped in places, one result of which was the Vizcaina pivotal fault (footnote 2, 447–454). The older fracture system thus resulting comprises 90 per cent of the fractures in the Pachuca district, and includes many of its major veins.

After this early, dip-slip fault system was formed, it was acted upon by a force presumably unconnected with the major intrusive, now emplaced, consolidated and inert. This force was a nearly horizontal shove originating east of Real del Monte and directed toward that area in a direction south of west. This compressive stress tended to deform the Real del Monte area, *i.e.*, to shorten it in a direction parallel to that of the force, and to lengthen it in a direction perpendicular to that of the force. But finding, in northern Real del Monte, a set of old northwest faults already more or less gouge-lubricated by primary, major dip-slip fault movements, the force from the east utilized these handy rupture surfaces and turned them into *disruptive faults*, the movement on which was nearly horizontal and north side west. (For a discussion of deformation without loss of cohesion of the unit mass deformed, marked by flow and the formation of antithetic faults, and deformation with loss of cohesion, marked by the formation of disruptive faults, see footnote 4, pp. 88–89.)

Had friction on these northwest disruptive faults been zero, no horizontal shearing stress would have been set up; the blocks between the faults would simply have been shoved westward, although probably differentially owing to uneven application of the shove. But several of these northwest faults show marked irregularity in strike within limited stretches, and the irregular stretch on one fault is about opposite that on the next (footnote 2, Figs. 2, 6). The irregular stretches on the northwest faults are thus contained in a belt transverse to the faults, long in comparison with its width, and trending just east of north. Within this belt, and nowhere else in the district, lie the Real del Monte north-south veins. These veins dip steeply, either east or west, but they show no fan structure in cross section (footnote 2, Fig. 8). They are uniformly displaced, north side west, by the northwest faults, regardless of whether the north-south veins dip east or west. This simple fact offers the main proof that their displacement was essentially horizontal (footnote 2, Fig. 7 and pp. 459–461).

The north-south fractures strike parallel south of the Gran Compaña northwest fault; but near that fault and north of it they fan out toward the north in a manner suggesting counterclockwise rotation. They show commonly marked fault drag toward the west near several northwest faults (footnote 2, Figs. 6, 12).

Where movement along a disruptive fault is impeded or halted a rotational or shearing stress is set up; deformation with loss of cohesion (disruption) is halted, and replaced by deformation with retention of cohesion (flow). Rotation of the north-south fractures, and the extreme fault drag are signs of rock flow. The ground in northern Real del Monte tended to flow under the influence of a counterclockwise shearing stress induced by impedence to disruptive faulting offered by the irregular stretches on the Gran Compaña and other northwest faults. The rotating north-south fractures are *antithetic* faults set up by the shearing stress. The slight horizontal displacements on these faults originated through rotation of the fault planes themselves (footnote 2, Fig. 3a and pp. 466–481, footnote 4, pp. 89–92).

The Vizcaina fault is the southernmost of the old northwest fracture set in Real del Monte (footnote 2, Fig. 2). South of it a strong southwest fault, the Santa Gertrudis, displaces north-south and other fractures nearly horizontally and in the direction, southeast side southwest. The supposed origin of this fault cannot be discussed here (footnote 2, pp. 475–476), but it probably formed in connection with the horizontal compressive stress from the east. By the aid of this fault the ground southeast of it moved southwest.

Stress from the east acting on northwest faults, in northern Real del Monte, and on the major southwest fault, in southern Real del Monte, would naturally induce the respective horizontal fault movements for northern and southern Real del Monte just described. Another factor may have greatly aided such movements. Two areas of volcanic conduits with local flows outpoured from them exist in the Pachuca district, one in the northwest corner, north of the town of Pachuca and along the northwest prolongation of the northwest faults of northern Real del Monte, the other near the southeast corner and roughly along the southwest prolongation of the Santa Gertrudis fault (footnote 2, Fig. 2). Evidence suggests that these areas became loci of low density, of crustal weakness, after extrusion of the flows that passed up their conduits. Compressive stress from the east would shove the ground with little hindrance along belts guided toward these weak areas respectively by the northwest faults of northern Real del Monte, and by the southwest Santa Gertrudis fault.

The ground between these belts would be stronger and would serve as a sort of buttress resisting the stress from the east; the flow of ground would swing around the north and south sides of this buttress toward the respective loci of weakness.

In the Pachuca area proper, and along a line connecting the two weak areas, is strung a series of east-west vein-fractures (Tajo, Analcos etc., foot note 2, Fig. 2, also pp. 483–484). Field evidence suggests a younger age for these fractures than that of fractures of the similarly oriented system surrounding them. Fig. 19, reference 2, a cross section of two such younger faults,

shows the latter to be step-faults, separating tilted blocks (antithetic faults, whose displacement is due to rotation of the fault planes themselves). These fault movements are entirely in the direction of dip. Antithetic faulting requires lateral elbow room to function (footnote 2, Fig. 3a). The suggestion is that the areas of crustal weakness, one at either end of this band of step-faults, provided such elbow room.

Mineralization affected, to a greater or less degree, all the faults and fractures mentioned above. The older fracture system contains important and productive veins (footnote 3, Fig. 2) which show ore control conditioned by dip-slip fault movements. The Tajo, Analcos and other east-west dip-slip faults of that series are important veins. The Real del Monte north-south veins, while of great importance, may not have produced in the aggregate any more ore than have the east-west, dip-slip faults.

Such was the picture in my mind when I wrote the papers cited. The twisted version given by Mr. Thornburg came as a shock.

Thornburg Paper. His version of my published and unpublished conceptions on Pachuca may be gathered from the following excerpts.

> In order to clarify the terminology used in this discussion, it should be explained that "normal fault rupture" is the term used in referring to the type of fracturing that takes place in the process of normal faulting or the settling of earth blocks due to gravitational force. . . . Compressive stress is the term used here in referring to the theory that the north-south fractures were formed and that transverse (northwesterly to east-west) fractures were squeezed open by east-west compression, which is not in accord with the conception of tensional rupturing presented here (pp. 283–284).

This would seem to imply I thought the east-west fractures not formed by the east-west compression, but merely squeezed open, later, by that stress. But this is not certain, so I try again.

> A large-scale horizontal projection showing the main fractures of the Real del Monte area, including those that are poorly mineralized as well as the productive veins, suggests that the subregional pattern formed by the north-south and transverse veins might be the result of compressive stresses applied horizontally operating in a more or less horizontal plane (p. 285).

The only large-scale horizontal projection I know of was made by myself, and it shows, not only the Real del Monte area but the entire district as well, with displacements of rock formations by faults, of such nature and direction that they could only have resulted from dip-slip movements. The omission is regrettable from the standpoint of fair play, for Mr. Thornburg implies rather strongly in this quotation that I believe the east-west faults were formed by horizontal compression.

He turns suggestion into plain statement in the following:

> Those holding the opinion that the pre-mineral fractures were formed by compressive, horizonal movements believe that the mineralization of the north-south and transverse fractures was contemporaneous; because this theory necessitates the assumption that the fractures of both systems were open to mineralization during

the same period. But it is difficult to conceive of all of the transverse fractures in the heart of Real del Monte as having been open during the time that veins of the north-south system were formed. An outstanding feature of Real del Monte is that the vertical range of ore on the north-south veins is greater and much deeper than that of transverse veins right in the same general locality. Moreover, the difference in mineralogical characteristics between veins of the two systems is manifest. . . . If the transverse fractures had been open to solutions at the same time the nearby north-south fractures were, one would expect them to have the same type of mineralization as the north-south veins, and to be mineralized over more or less the same vertical range. This disparity alone is an obstacle to the acceptance of the theory that the mineralized fractures were formed by horizontal compressive stress, and it should be pointed out, as a matter of constructive criticism, that the exponents of the compressive theory have not explained it (p. 286).

Mr. Thornburg makes it clear on page 285 that I am the main exponent of this extraordinary theory. All pre-mineral fractures at Real del Monte, the transverse (northwest) as well as the north-south vein-fractures, were "formed by compressive, horizontal movements." A stress can form a fracture; a movement can't form anything but a movement. But how fractures of both systems (at right angles to one another) could be "open to mineralization during the same period" under a single compressive stress acting horizontally is beyond me. If the stress "squeezed open" the northwest (transverse) fractures, as ascribed to the "compressive stress theory" in the first quotation above, then it acted to squeeze shut the north-south fractures. In my recapitulation above I have described the northwest faults as tight, gougy disruptive faults at the time of formation of the north-south vein-fractures. But they were dip-slip faults, originally, of the older system, hence were on hand to receive any early mineralization before they became disruptive faults. Further, some of them made openings by zig-zag ore control at the time of the horizontal stress, and received ore shoots in the openings (Fig. 14 of footnote 2). Finally, those older northwest fractures that did not become disruptive faults were on hand to receive metallization before, during, and possibly after, metallization of the north-south fractures. Hence there is nothing in my theory requiring simultaneous metallization of north-south and transverse fractures.

I shall complete the exposition of Thornburg's concept by a final quotation:

> . . . it is evident from private reports that, as geological studies proceeded, two distinct lines of thought were being expressed, namely (1) that pre-mineral fracturing in general was caused by subsidence on a large scale, and (2) that the north-south fractures developed contemporaneously with concomitant transverse fractures as a result of compressive stress. Wisser expanded the latter theory in far greater detail than any previous geologist. . . .

Mr. Thornburg implies that the present writer took horizontal scratches in soft gouge as indicative of premineral major fault movements. The dominant direction of striæ for the district is of course in the direction of dip, since over 90 per cent of the faulting was in that direction. I have seen plenty of strong mullions, often silicified or quartz-encrusted, pointing down the dip.

I have seen entirely similar mullions in the following places (Fig. 6 of footnote 2 for locations).

1. Santa Gertrudis fault near Santa Inés vein, 500 m. level. Silicified mullions down 17° SW.

2. Branch of Santa Gertrudis fault near the same place: mullions down 25° W.

3. San Pablo fault near Colón and Dios te Guie veins, strong striae horizontal.

4. Vizcaina fault near Colón vein, silicified striae horizontal.

5. San Sabás vein north of Vizcaina, striae horizontal.

6. Gran Compaña fault near Purísima vein, striae horizontal. Many other localities are recorded on the field sheets deposited in Mr. Thornburg's office at Pachuca.

Mr. Thornburg's examples will now be discussed.

Ideal Diagram. Mr. Thornburg's ideal diagram, his Fig. 1, is reproduced roughly in the accompanying Fig. A. His caption is: "Fig 1.—Ideal-

FIG. A
Thornburg Ideal Diagram

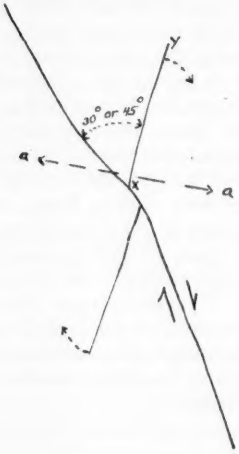

FIG. B
Feather Joints

ized block diagram showing tensional effect related to normal fault type of rupturing."

Describing the diagram, Mr. Thornburg says:

> Steeply dipping hanging wall and footwall fractures which strike more or less parallel to the main inclined plane of normal movement are recognized here and elsewhere as common characteristics of the normal fault type of rupture of rock

formations. These are parasitic branch fractures formed by tensional forces set up along and near the main plane of movement and they gradually diminish and fade out as they extend outward into the walls.

His branches, then, are caused by tension genetically connected with fault movements along the parent fault. The only type of tension possible in the formation of such branches is that connected with shearing stress along the parent fault.

Kent's Mechanical Engineers' Handbook, 1923 edition, defines shear as follows: "The internal force acting along a plane between adjacent parts of a body when two equal forces parallel to the plane considered act on each part in opposite directions. The shear resists the tendency of one part to glide over the other part." Fundamental definitions form a good antidote to loose thinking, and this one emphasizes the fact that shear is a *stress*, not a gliding of one fault block past its neighbor.

"Normal faulting," or any other kind of faulting, therefore, cannot produce "tension branches" unless there is hindrance to the fault movement and a shearing stress set up (Fig. B). Tension branches genetically connected with hindered fault movements are commonly known as feather joints.[5] As shown in Fig. B, these branches are fissures whose walls are pulled apart by the tensional component of the shearing stress (a-a, Fig. B). The more hindered the movement, the greater the shear and tension, and the bigger the feather joint.

Clay experiments and many field examples show that the initial angle between parent fault and feather joint is remarkably constant. Where fault and branch form through a single stress, this angle is very close to 30°; where the branch formed in connection with impeded movement along a pre-existing fault plane, the angle approximates 45°. The reason for this will be set forth in a forthcoming monograph.

Shearing stress is rotational stress, and in soft rock results in rotational strain. In Fig. B, shearing stress in soft rock induces flow near the fault. Point x on the fault plane either moves more slowly than does point y on the feather joint, or it does not move at all. The result is rotation of the feather joint, whereby the angle between joint and parent fault increases over its initial value of 30° or 45°. Feather joints however are fissures, and commonly require for formation rock too competent to flow. In this case the feather joints do not rotate, but retain their initial angles with the parent fault. But in no case are these angles, in the writer's experience, less than 30° for the one case, or 45° for the other. The mechanics of Fig. B show that feather joints may never bend around toward, or rejoin, their parent fault.

Thornburg's Fig. 1, reproduced in Fig. A, shows his "tension splits" with a pronounced tendency to turn back toward their parent fault, and indeed he remarks on this tendency (p. 297). Nevertheless the branches in his ideal diagram, as drawn, might possibly be feather joints. (He even shows a hump in the parent fault to hinder fault movements, with the branches local-

[5] Ernst Cloos: "Feather joints" as indicators of the direction of movements on faults, thrusts, joints and magmatic contacts. Proc. National Acad. Sci., vol. 18, 5 (May, 1932), 387–395.

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ized near the hump.) Unfortunately his field examples, with one exception, do not deal with tension splits genetically connected with hindered dip-slip movement.

Case I. The vein strikes northwest and dips northeast. There is therefore no reason why fault movement connected with it should not have been in the direction of dip. Mr. Thornburg's Fig. 2 does nothing to prove this, however. His dip-splits leave their parent fault at initial angles of 15° and almost at once turn parallel to the parent fault. Several types of stress might have formed these branches and kept them open for vein-formation, but certainly not shearing stress connected with dip-faulting on the parent fault.

Case II. Here again the parent vein belongs with the older fracture system, and ore localization connected with dip-faulting might be expected. But the "typical tension cracks" in the vein footwall parallel too closely the main vein to be feather joints. In this case (Fig. 3a) one of the "tension cracks" actually rejoins the main vein at depth, truly a *reductio ad absurdam.*

Cases III, IV. These relate to the same east-west vein, on which dip-faulting may be expected as with previous examples of the same fracture set. Fig. 6, Case III, shows a real feather joint (the only one in the six examples given). It makes an angle of 50° with its parent fault, suggesting its formation by shearing stress acting in a vertical plane along a preexisting fault surface. Fig. 7, Case IV, however, shows the pseudo-feather joints of the other examples. The vein simply splits complexly going downward, like a wishbone; angles between the splits are very small.

Case V. The only one of the six dealing with a north-south vein. Fig. 8 shows that the main "footwall split" is the downward continuation of the unsplit vein in the upper levels. This downward extension peters out in depth, but some 25 meters out in its hanging wall a strictly parallel vein appears to have carried ore. This is the familiar *en echelon* arrangement of veins in a sheeted zone, an arrangement apparent in section instead of plan. Mr. Thornburg links the hanging wall vein with the footwall vein by means of a narrow, flat-dipping stringer. The resulting dog-leg he calls the "main vein." But for the hanging wall block of this "main vein" to have wrapped itself around this dog-leg in descending in the manner postulated calls for rock flowage far beyond that ever asked for by the present writer. Or admit this impossibility. Then why should the strong hanging wall vein, dipping 80°, be called the main or parent fault, and the footwall vein, dipping 80° in the same direction, be called a tension joint? The reaction of a fracture to a definitely oriented stress (in this case, the dip-slip postulated) depends on its attitude with relation to the direction of stress

Case VI. The vein strikes east and dips flatly south, so that dip-faulting would be expected. The "tension joints" shown in Fig. 9 are of the same type exemplified in all but one of the examples. They are not tension joints.

"Normal Faults" and "Subsidence." Mr. Thornburg offers no definite alternative to my discarded theory concerning tectonics at Pachuca, but hints (p. 285 and p. 287) that the fracture system there developed through large scale "subsidence" and resulting "tensional rupture." Some such theory appears to have been subscribed to, or originated by, Dr. Warren J. Mead (p.

287). I may be doing to Mr. Thornburg what he has done to me, in the following discussion, *i.e.*, setting up an imaginary straw man and knocking it down, but I offer the discussion nevertheless because I think it contains truth, whatever the views of Messrs. Mead and Thornburg may be.

It seems to me extremely doubtful whether any regional fault pattern is formed by subsidence, although fault displacements may be reversed or accentuated by that agency. The Tectonic Map of the United States and many oil field structural studies show, for regions of domes and basins, that faulting, or any fracturing is largely confined to domal or anticlinal uplifts, with the basins between devoid of fractures and showing instead minor anticlinal wrinkles. Note especially the San Juan basin on the Tectonic Map.

The writer while at the Johns Hopkins University assisted Ernst Cloos in performing the following experiment. A cake of moist clay was molded in the form of an arch, like an assay muffle, over an ordinary rubber hot-water bag laid flat and inflated with air. The bag was then slowly deflated by release of air. A zone of parallel cracks soon appeared along the crests of each of two parallel anticlines on either side of the sagging center of the bag. These cracks soon increased in number and size, and showed their character of "normal faults." Most of these dipped away from the growing "graben," and with continued deflation and sinking of the graben the fault planes rotated toward the void; the rotation produced the "normal" displacement. These are antithetic faults. Some of the anticlinal faults however dipped toward the "graben"; here the footwall block dropped by gliding along the fault plane, without rotation of that plane. These are synthetic faults.

Next similar fault zones developed along the other two sides of the sinking basin (top and bottom of the deflating bag). All these faults were confined to the flanks of the basin; these flanks are, relatively, uplifts. Within the basin, after sagging became pronounced, radial folds developed (San Juan basin of Tectonic Map), with the center of radiation the center or deepest part of the basin.

These radial folds are the analogues of radial tension fissures developed on a domal uplift. Instead of expressing tension, stretching, they express compression directed centripetally toward the center of the basin. Material within and around a sagging basin tends to flow from the rims toward the center. "Disruption" means a rupture, a rent, a breach, according to the dictionary. With vertical forces, disruption may be caused by stretching during uplift, or by shear acting in a vertical plane; seldom or never by gravity alone. Settlement of a segment of the crust over a semi-void involves the opposite of disruption, of a pulling-apart; it involves a coming-together.

The unsafe use of the term "normal fault" with implications of "tension" and "subsidence" has been pointed out. With antithetic faults, whose displacement is due solely to rotation of the fault plane ("block-toppling," whether in plan or section), the footwall moves "up" as much as the hanging wall moves "down" (Fig. 3a, footnote 2). With many "normal" faults where rotation is not involved, the writer believes that the footwall actually moved up, with reference to a fixed horizon in space, while the hanging wall either

remained stationary or moved down only slightly. In such cases no "tension" or "subsidence" is involved, only an upward shove of the footwall.

The writer is not original in this belief. Longwell[6] has this to say: "Many geologists indicate presumed dip-slip movement by the terms normal and reverse; if there is direct evidence of strike-slip, these geologists speak of a *strike-slip* fault, regardless of geometric relations among beds or other features affected. Billings tacitly acknowledges this common usage by the title of his Chapter 11: 'Gravity or Normal Faults.' If the two terms are interchangeable why not use *normal*, and avoid the implication, which lurks persistently in spite of printed definitions, that the hanging wall of every such fault has actually moved downward in response to gravity? If this origin could be demonstrated generally, the term *gravity fault* would be justified as part of a truly genetic classification. However if we except local 'landslide' faults, and certain other faults in special geologic settings, it must be admitted that the exact role played by gravity in causing movement on faults is difficult to establish. On the other hand it is conceivable that differential forces responsible for plateau uplift may set up shearing stresses that result in large normal faults, along which the footwall blocks move to higher elevations than the adjacent hanging wall blocks. Under the assumed conditions gravity has no part in the faulting—except to resist the uplifting forces."

EDWARD WISSER.

SAN FRANCISCO,
October 1, 1945.

*VETERANS' RETRAINING PROGRAM IN GEOLOGY.**

Sir: During the past five years it is estimated that the armed forces absorbed some fifteen hundred young American geologists of graduate, near-graduate, or post-graduate status, only a small number of whom had gained any experience in professional application of their learning.

During their terms in the armed forces few of these young men have had the opportunity of using their geological training or of acquiring additional geologic knowledge. It may therefore be assumed that they have suffered considerable loss of geologic skill and knowledge and are thus not prepared to resume their studies or professional activities in competition with those geologists whose careers have not been interrupted by the war.

Because of this situation and the current demand for trained geologists, the U. S. Geological Survey proposes to undertake a program of training in the form of supervised field, laboratory, and office work that will enable discharged veterans to adjust themselves more quickly and with more confidence in resuming their careers. The Survey proposes to undertake only this applied phase of the retraining. It recognizes that many of the expected trainees will require preliminary academic courses in college or university

[6] Chester R. Longwell: Review of "Structural Geology" by M. P. Billings. ECONOMIC GEOLOGY, XXXVIII, 4 (June–July 1943), 327–328.

* Published by permission of the Director of the Geological Survey.

geology departments that are equipped to give concentrated courses of graduate calibre.

The proposed dual program has been discussed with heads of the geology departments of the Universities of Chicago, Columbia, Harvard, Johns Hopkins, Princeton, and Yale; and they have indicated their approval of the plan in principle. Heads of geology departments in other schools interested in participating in this phase of the program may obtain pertinent information from the heads of the geology departments of those universities. Further information concerning the Geological Survey's phase of the program may be obtained by writing to W. H. Bradley, Chief Geologist, Geological Survey, Washington 25, D. C.

The instruction of qualified veterans in participating schools will, insofar as is feasible, be adjusted to the specific needs and interests of the individual to better equip him to undertake and benefit by Survey or other professional experience in field, laboratory, and office work during the 1946 field season.

Candidates for these temporary appointments to the Geological Survey will be selected on a competitive basis through the channels of the Civil Service Commission, and in accord with veterans' preference policies. It is hoped, however, that veterans who apply will have had the benefit of the preparatory college or university retraining before they seek appointment.

The number of veterans which the Survey will be able to absorb will depend upon the amount of funds appropriated to the Survey for geologic investigations. An estimate of the size of the field program should be available by spring after the House reports out the appropriation bill. As many as possible of the most competent temporary appointees will be given the opportunity of accepting more permanent appointments on the Geological Survey staff, or will be given aid in obtaining appointments in other governmental agencies or in industry.

This dual program will operate on a very flexible basis, to take care of all individual cases, involving individuals whose academic training and professional experience to date lie within a rather wide range. It will be fitted also to individual desires, to allow for academic training only, for Survey experience only, or for both, depending on the qualifications and wishes of the individual.

W. H. BRADLEY,
Chief Geologist.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
January 1, 1946.

REVIEWS*

Pyrite Deposits of Missouri. By O. R. GRAWE. Mo. Geol. Survey, Vol. XXX, 2d Series, 1945. 482 pp. 1 map, 2 tables in pocket.

This rather elaborate volume, printed in the usual excellent style of its series, provides much the most complete factual description of one unique group of the varied mineral deposits of the Mississippi Valley which, hitherto, has not been widely known nor well understood.

Pyrite occurs in Missouri in several types of deposits, all of which are covered in the report, but the ones of principal importance are those associated with sink structures of the Central Ozark plateau and sometimes rather inaccurately called filled sinks. Since 1900, and chiefly since 1930, these have produced 250,000 tons of commercial pyrite, mostly marcasite admixed with some pyrite. Opened originally for iron ore, the same group of deposits yielded in the preceding century perhaps ten times as much commercial iron ore, chiefly hematite. As iron ore deposits they have been treated in previous reports of the Missouri Survey, but the present volume is the first to deal adequately with the primary sulphides from which the iron ores were derived, and the first to apply to either type in any detail the technique of microscopic study of polished sections.

The structures in which the ores occur are generally centroclinal, and are due to the removal of underlying limestone in solution, permitting the collapse of overlying formations. The dips produced commonly range from 10° to 30°, rarely even 90°, quite anomalous in an area of normally flat-lying rocks. The sinks are concentrated almost entirely at one horizon, the contact of the Gasconade dolomitic limestone with the overlying Roubidoux sandstone. Apparently the Roubidoux, an excellent aquifer, was at some past period a horizon of active water circulation under conditions that favored solution of the underlying limestone at points determined by minor details of folding and faulting. The slumping of the overlying formations generally results in a sandstone rim around the sinks. All students of the sinks have agreed that they are the work of ground water, probably of ordinary meteoric origin. The author believes that the sinks were formed very near the former land surface and at or above the water table at the time of formation. His statement of the matter is as follows:

"These structures were formed at or above the ground-water surface where circulation was active and where the water was not yet saturated with the products of its corrosive action" (p. 82–, also p. 183).

In further support of this opinion he points out that underground caverns are abundant in the region near the present land surface, and are now occupied by streams that carry large amounts of limestone and silica in solution or suspension. Hence, he assumes the caverns have been formed chiefly by these present streams.

There is good ground to doubt this conclusion, however, and the matter has some bearing on the later theory of genesis proposed for the sulphide ores. Bretz [1]

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

[1] Bretz, J. Harlan: Vadose and phreatic features of limestone caverns. Jour. Geol., Aug.–Sept., 1942. Vol. L, pp. 675–811.

has published recently an elaborate study of the origin of accessible limestone caverns in many places, including several from this particular region, and has reached the conclusion that large caverns of this type are almost never the work of the streams found occupying them after their exposure, but rather of a deeper and earlier groundwater circulation that occurred beneath the water table, or under phreatic and not vadose conditions. Exposure to the surface results in an episode of filling by débris, chiefly clay, and the development of a later vadose circulation that produces minor enlargement of the caverns, but primarily they could not have originated by such a process.

The mineralized sinks seem to lack this episode of clay filling. Moreover Mr. Grawe himself in another section adduces good evidence that they could not have been directly connected to the surface during the time of their enlargement nor until after the close of sulphide mineralization.

"That the pyrites was not deposited in open surface sinks but in subterranean caves also is suggested by other features of these deposits. The high purity of the ore itself, its freedom from surface débris, suggests that the sink structures were not open" (p. 80).

It is difficult to believe that ground water acting entirely at or above the water table could have produced a whole group of sinks free of any evidence of surface connection at the time of formation. The age of the sinks likewise is a matter in dispute. Some have attributed them to an ancient erosion interval corresponding to the prominent unconformity that separates Mississippian and Pennsylvanian in Missouri and adjacent states. That some sinks were formed at that time is evidenced by sink-like pockets filled with coal, fireclay, etc. in this same region.[2] There evidently were sinks that did have a surface expression in Pennsylvanian time. Mr. Grawe, however, advocates the view that the iron-filled sinks did not develop until the Pennsylvanian shales and sandstones were being eroded, supposedly at the time the so-called Salem platform or Ozark peneplain was developed, probably in the Mesozoic.

Reserving further comment on this subject until later, let us turn to the data on paragenesis. This naturally involves two phases: (1) the primary sulphides and (2) the oxidized iron ores.

The primary sulphide consists predominantly of fine-grained, sooty black marcasite. In its firmer phases this exhibits many radial, botryoidal and even stalactic structures. Finely crystalline pyrite in considerable amount was deposited later, on and over the marcasite. A very little chalcopyrite cuts both pyrite and marcasite, but, for the most part, Mr. Grawe seems to think this is supergene. It is hard to avoid the conclusion, however, that some primary copper sulphide must have existed, a point not adequately considered.

Mr. Grawe believes that the heavy deposition of early marcasite indicates a strongly acid condition at the beginning of sulphide mineralization later tempered to permit pyrite deposition. He infers that the radial and botryoidal structures in marcasite indicate deposition from colloidal solutions. Probably nearly everyone will accept these conclusions. The marcasite and pyrite seem to have crystallized very slowly in fine but uneven texture from a very concentrated sort of sulphide gel. The details of structure and crystallization are illustrated by excellent photomicrographs.

The oxide iron ore consists mainly of red earthy hematite with some goethite and some finely crystalline specularite. Considerable quartz was formed during the oxidation period, including a little amethyst. Because of the specularite and

[2] McQueen, H. S.: Geology of the fire clay districts of East Central Missouri. Mo. Geol. Surv., Series 2, Vol. XXVIII, 1943.

the amethyst it has been suggested that these ores may be magmatic in origin; or again that the heat supposedly necessary for their development may have been generated by the oxidation of the sulphides. Mr. Grawe rejects both these explanations for seemingly good reasons.

That the oxides have formed under ordinary atmospheric conditions is indicated by the fact that their location is related in all cases to the present ground water level. Above water level the ores are oxidized; below, unaltered marcasite and pyrite are found. The transition zone is only a few feet in thickness. Where the water table is low in relation to the deposits oxidation has been complete and no sulphide remains. Where the deposits are relatively deep, oxidation has not reached the deposits and only sulphide occurs. As the production figures show, however, the bulk of the deposits in most cases had been oxidized. Mr. Grawe finds no evidence that the oxidation going on at ground water level is rapid enough to raise the earth temperature appreciably, although when sulphides are exposed to the air in mining, and the water is drained, heating may be considerable.

Paragenetically the oxides are later than sulphides as shown by pseudomorphism of hematite after marcasite and pyrite. Malachite and azurite formed in minor quantities where copper was present, and in several cases deposits were opened, unsuccessfully, as copper mines on the strength of these carbonates. Chalcopyrite is found occasionally in the hematite near water level, a supergene redeposition under the influence of adjacent sulphides, Mr. Grawe believes. Quartz is intergrown with and colored by the iron oxides, and in the upper part of the unoxidized zone occasionally replaces sulphides.

Mr. Grawe's evidence as to the oxide ores probably should suffice to convince even the skeptical of their supergene origin. When it comes to primary sulphides, however, there is likely to be less unanimity for he adheres valiantly to the position long maintained by the Missouri Geological Survey that these sulphide ores were formed by cold descending ground waters. He even extends this interpretation (pp. 211–214) to the complex cobalt-nickel-lead-zinc ores of southeastern Missouri.

If Mr. Grawe's position were restricted to the marcasite-pyrite ores alone it would seem easier to defend. Admittedly iron and sulphur are ubiquitous substances, and the widespread occurrence of pyrite disseminated in sedimentary formations, and especially in coal beds, poses a difficult problem for explanation in terms of magmatic processes as understood at present.

However, the remarkably high concentration of iron sulphide in the sinks; the evidence that it probably formed in one brief episode never repeated; and the failure to find the suggested process of formation in operation at the present time; these and other factors, to many geologists, will render the supergene explanation suspect.

Mr. Grawe believes that the sinks were formed in post-Pennsylvanian time, and that iron in oxide form obtained from overlying formations, chiefly the Pennsylvanian shales, was carried down into the water-filled openings where it reacted with H_2S that had been generated, probably by organic processes, during the long period when the strata were deeply buried.

Dissenters will point out that many sinks developed in near-by areas in pre-Pennsylvanian time and that those which were open became filled with coal, fireclay, etc. They will wonder if these iron-filled sinks did not develop likewise at that time but, due to a firm roof of protective sandstone, were not open, so remained for long ages filled only with water, while Pennsylvanian strata of great thickness covered the region. In this condition magmatic processes could then have introduced the iron sulphide, filling the caverns with intensely acid solutions

which attacked walls and roof, and often caused the roof to slump down into the depositing sulphide bodies. Subsequent erosion and exposure then led to oxidation as already explained.

Mr. Grawe has devoted considerable space to spectographic and x-ray investigations of the minor elements in the pyrites and associated oxide iron ores in an effort to shed light on the problem of supergene versus magmatic origin. It is interesting to note that his findings support his own conclusions to his satisfaction. To the reviewer this result, in connection with the opposite findings of various investigators in other cases, casts some doubt on the validity of this line of evidence either one way or the other.

Much space is devoted to data chiefly of local value describing individual mines and prospects. An interesting section deals with the economics of pyrites mining. The greatest period of expansion, from 1932 to 1940, was the result of economic depression. Acid-producing zinc smelters in the St. Louis area were forced to curtail spelter production and turned to pyrites as a cheap means of fulfilling their contracts for acid. When the demand for zinc returned, in 1940, they again switched to sphalerite, and pyrite mining ceased.

The book appears needlessly long for the ground covered and it seems that better organization and editing might have reduced it considerably. As one example, the structural conditions attending the mineralized sinks are described in very similar terms at least five times (pp. 42, 65, 75, 89, 172). In spite of these minor criticisms the book is an interesting and valuable contribution.

BALMAT, N. Y.,
Dec. 13, 1945.

JOHN S. BROWN.

Uranium and Atomic Power. By JACK DEMENT AND H. C. DAKE. Pp. 343. Chemical Publishing Co., Brooklyn, N. Y., 1945. Price, $4.00.

This timely book by an eminent research chemist and author, and well known mineralogist, presents all of the underlying principles and theories relating to the atomic bomb and atomic power, in language that everyone can understand. The layman, chemist, and student can get from this book all of the information regarding atomic power which he has been thirsting to know. The reader need not be afraid that he cannot understand it, because the authors have given the underlying principles that the layman, the technical man and the physicist can comprehend. The story of uranium is unfolded; its chemistry is set forth and U235 no longer need have its secrets. The book is timely and interesting.

Rocks and Rivers. By ELLIS W. SHULER. Pp. 300; figs. 100. Jaques Cattell Press, Lancaster, Pa., 1945. Price, $4.00.

This nicely illustrated book conveys the author's love of earth lore. It deals with landscapes and rocks and soils, chiefly the things one sees and how they were formed, interpreted by a scientist for the lay reader. His enthusiasm for landscapes and the manner in which they were carved is transmitted to the reader in a dramatic and artistic manner. It is not meant to be a text book but cultural reading about the earth's crust, its rocks, its rivers and canyons and springs and shore features.

Indian Mining. By J. A. DUNN. Pp. 262; figs. 21; tables. Mining, Geological and Metallurgical Institute of India, 1943.

This pocket book covers questions regarding mining in India that might be raised by mining companies, importers, bankers and engineers. It is also a pocket

text book. It covers uses, distribution, testing of minerals; sampling, and estimation of reserves; mining methods, arts, processing, marketing and prices; mine valuation and valuation tables; taxation, tariffs, and legal aspects. It is a valuable reference volume.

Our Oil Resources. Edited by L. M. FANNING. Pp. 331; figs. 4. McGraw-Hill Book Co., New York, 1945. Price, $4.00.

An exhaustive study of our oil resources by a group of highly qualified authorities, including eleven top executives of outstanding oil companies. The best idea of its contents may be gained from a list of chapters and authors: I. Role of Private Enterprise in the Development of Oil Resources by John A. Brown; II. American Oil Companies in Foreign Petroleum Operations by Eugene Holman; III. Conservation of Oil and Gas Resources by J. C. Hunter; IV. Technology—the Great Multiplier, Pt. 1, Exploration Technology by O. D. Donnell, Pt. 2, Production Technology by John M. Lovejoy, Pt. 3, Refining Technology by Robert E. Wilson; V. Oil and Natural Gas Reserves, Pt. 1, The Earth's Petroleum Resources by Wallace E. Pratt, Pt. 2, Estimate of U. S. Oil Reserves by the American Petroleum Institute, Pt. 3, Natural Gas Resources by Lyon F. Terry, Pt. 4, Cost of Storage of Military Reserves of Crude Petroleum or Products by F. W. Abrams; VI. Reserves of Coal and Shale by K. C. Heald; VII. Oil from Coal and Shale by Robert E. Wilson; VIII. Oil in Public Domain, Naval Reserves, and Federal and State Marginal Lands, Pt. 1, Public Domain and Naval Reserves by W. H. Ferguson, Pt. 2, Lands of the U. S. by A. C. Mattei, Pt. 3, Status of Federal Lands by L. T. Barrow; IX. Capital Employed in Petroleum Industry by Joseph E. Pogue; X. American Oil Industry by Leonard M. Fanning.

The book points out the role of petroleum in modern industrial life and discloses the part played by private companies in our petroleum industry. It is an outstanding and impressive symposium by outstanding talent.

BOOKS RECEIVED.

RICHARD J. ORDWAY.

The Diamond Industry in 1944—20th Annual Review. S. H. BALL. Jewelers' Circular—Keystone. New York. The usual excellent review.

I. Subsurface Relations of the Maquoketa and "Trenton" Formations in Illinois. E. P. DUBOIS. **II. Petroleum Possibilities of Maquoketa and "Trenton" in Illinois.** C. A. BAYS. Pp. 38; figs. 10; pls. 2. Ill. State Geol. Sur. Rep. of Invest.—No. 105. Urbana, 1945. I is a brief discussion of subsurface stratigraphy and relations of the Maquoketa, Galena, Decorah, Plattin, Joachim, and Dutchtown formations in Illinois. II recommends southwestern portion of Ill. for exploration of sandstones of Maquoketa formations, and areas of secondary permeability in Galena formation.

A Major Buried Valley in East-central Illinois and Its Regional Relationships. L. HORBERG. Pp. 349–359; figs. 4; tables 1. Ill. State Geol. Sur. Rep. of Invest.—No. 106. Urbana, 1945.

Molecular Associatons between Montmorillonite and Some Polyfunctional Organic Liquids. W. F. BRADLEY. Pp. 5–12; figs. 5; tables 2. Ill. State Geol. Sur. Rep. of Invest.—No. 108. Urbana, 1945. Association of polyfunctional saturated aliphatic chains with montmorillonite surfaces gives evidence of augmented attraction of C–H . . . O bond between methylene groups and the oxygen surfaces of the clay. Oxygen surfaces exercise a lesser influence on some aromatic rings.

Coke from Illinois Coals, an Experimental Slot-type Oven. F. H. Reed, H. W. Jackman, and P. W. Henline. Pp. 5–18; figs. 6; tables 3. Ill. State Geol. Sur. Rep. of Invest.—No. 107. Urbana, 1945. Study of substituting mid-western coals for some eastern high-volatile coals now used.

Oil and Gas Map of Illinois. A. H. Bell and David H. Swann. Scale 1/500,000. Ill. State Geol. Sur. 1945.

Recent Information on the Maxville Limestone. R. E. Lamborn. Pp. 18. Ohio Geol. Sur. Columbus, 1945. Source for thick deposits of high calcium limestone in eastern Ohio.

Exploration for Oil and Gas in Western Kansas during 1944. W. A. Ver Wiebe. Pp. 112; figs. 30; tables 35. Bull. 56, Kan. Geol. Sur. Lawrence, 1945. Some 1,508 test holes were drilled, of which 666 were oil wells and 98 gas wells. 53 new oil or gas pools discovered.

Ferruginous Bauxite Deposits in Northwestern Oregon. F. W. Libbey, W. D. Lowry, and R. S. Mason. Pp. 98; figs. 8; pls. 2; maps 8. Bull. 29, Dept. of Geol. and Min. Ind. Portland, Ore., 1945. Price $1.00. Deposits formed by laterization of Miocene basalts; topography governs outline and extent; thickness 6–20 feet. Treatment to produce both alumina and iron appears feasible. Deposits may become important future source of alumina. Favorable location to aluminum reduction plants on lower Columbia River.

Capitan Iron Deposits, Lincoln County, N. Mex. U. S. Bureau of Mines. Pp. 11; figs. 1; tables 2. War Min. Rep. 433. Wash., 1945. Considerable tonnage of easily-concentrated, low-grade, iron-bearing material low in deleterious elements. Deposit not now capable of profitable operation.

Tem Puite Tungsten District, Lincoln County, Nev. U. S. Bureau of Mines. Pp. 19; figs. 3. War Min. Rep. 430. Wash., 1945. Important potential source of tungsten with large known reserves.

New Mexico Potash, Eddy County, N. Mex. U. S. Bureau of Mines. Pp. 20; figs. 2; tables 5. War Min. Rep. 432. Wash., 1945. Indicated deposit contains 9,370,120 tons of minable potash ore, average 24.73% K_2O.

Apex Property, Coconino County, Ariz. U. S. Bureau of Mines. Pp. 8. War Min. Rep. 436. Wash., 1945. Copper mineralization in sandy-cherty Kaibab limestone. Sufficient tonnage to maintain present operations for one additional season. Results disappointing.

Kaolin from the Andersonville Area, Macon County, Ga. U. S. Bureau of Mines. Pp. 7; figs. 1; tables 3. War Min. Rep. 416. Wash., 1945. Large deposit of high-grade kaolin contains 10,000,000 tons of kaolin and 500,000 tons of good bauxite underlying kaolin.

Morelock Creek Area, Fort Gibbon District, Alaska. U. S. Bureau of Mines. Pp. 8; figs. 1. War Min. Rep. 406. Wash., 1945. Combined tin and gold content of placers too small for operation.

American Eagle Mine, Mariposa County, Calif. U. S. Bureau of Mines. Pp. 8; figs. 2. War. Min. Rep. 407. Wash., 1945. No zinc ore of commercial tenor.

Effect of the War upon Mining and Metallurgy in Arizona. U. S. Bureau of Mines. Pp. 34; figs. 9; tables 9. War Min. Rep. 403. Wash., 1945. Post-war outlook for base-metal mining in Arizona.

Treadway Deposit, Pulaski County, Ark. U. S. Bureau of Mines. Pp. 24; figs. 13; tables 2. War Min. Rep. 401. Wash., 1945. Commercially significant bauxite ore body.

Industrial Limestones and Dolomites in Virginia: New River—Roanoke River District. B. N. COOPER. Pp. 98; figs. 13; tables 2; pls. 11; Geol. Sec. 39. Bull. 62. Vir. Geol. Sur. University, 1944. Favorable quarry sites on large undeveloped deposits of high-calcium limestone and high-magnesium dolomite deposits, with tonnages.

Virginia's War Mineral Resources. A. BEVAN. Pp. 20. Vir. Geol. Sur. University, 1942.

Virginia's Industrial Limestones. A. BEVAN. Pp. 8. Vir. Geol. Sur. University, 1942.

Virginia's Mineral Industries. A. BEVAN. Pp. 14. Vir. Geol. Sur. University, 1938. Gives history. Good photographs.

Bibliography of the Geology and Mineral Resources of Utah, to Dec. 21, 1942. B. F. STRINGHAM. Pp. 99. Bull., U. of Utah, Salt Lake City, 1944.

California Journal of Mines and Geology. Pp. 179. Quar. Chap. of State Mineralogists Rep. XL. Div. of Mines. Sacramento, 1944. Three articles by W. J. Miller.

Geology and Ground-water Resources of the Coastal Area in Mississippi. G. F. BROWN, V. M. FOSTER, R. W. ADAMS, E. W. REED, AND H. D. PADGETT, JR. Pp. 231; figs. 23; pls. 14; tables 18. Bull. 60, Miss. State Geol. Sur. University, 1944. Decline of artesian yield in area.

The Structure of the Tertiaries near Gogha, Kathiawar. J. A. DUNN. Pp. 10; pls. 3; map. India Geol. Sur. Calcutta, 1942. Price Rc. 1. Study of structures that affect natural gas horizon.

Coal in Kathiawar. J. A. DUNN. Pp. 12; figs. 3. India Geol. Sur. Calcutta, 1942. Price As. 4. Indicates no payable seams.

Bulletins of Economic Minerals, No. 10—Mica. J. A. DUNN. Pp. 84; pls. 5. India Geol. Sur. Calcutta, 1942. Price Rs. 2–2. Report on Indian mica industry covering uses, occurrences, mining, cutting, marketing, production.

The Economic Geology and Mineral Resources of Bihar Province. J. A. DUNN. Pp. 238; index; figs. 2; pls. 1; tables 37. India Geol. Sur. Calcutta, 1942. Present position of mineral industry and developments that should be encouraged.

Presidential Address to Mining, Geological and Metallurgical Institute of India. J. A. DUNN. Pp. 19. Calcutta. Suggestions for the future organization of India's mineral industry. Foresees approach of nationalization of mineral industry.

The Stratigraphy of South Singhbhum. J. A. DUNN. Pp. 303–369; figs. 7; pls. 33–37. Memoirs of India Geol. Sur. Calcutta, 1940. Price Re. 1–14. Describes new Kolhan Series.

Manganese near Chaibasa, Singhbhum. J. A. DUNN. Records of India Geol. Sur., Vol. 74, Pt. 4. Pp. 467–473; figs. 1. 1939. Origin of deposits.

The Geology and Petrology of Eastern Singhbhum and Surrounding Areas. J. A. DUNN AND A. K. DEY. Pp. 281–456; figs. 7; pls. 24–40; geol. map, scale 1″–2 mi. India Geol. Sur. Calcutta, 1942. Describes rocks of Dhalbhum and adjacent areas. Summarizes knowledge of whole tract.

Welded Rhyolitic Tuffs or "Ignimbrites" in the Pasoemah Region, West Palembang, South Sumatra. J. WESTERVELD. Pp. 202–217; figs. 9; geol. map. Overdruk uit Leidsche Geologische Mededeelingen. 1942.

Three Geological Sections across South Sumatra. J. WESTERVELD. Pp. 1131–1139. Reprinted from Proceedings, Vol. XLIV, No. 9, 1941. Nederl. Akademie Van Wetenschappen.

Mineralisatie op de Tineilanden. J. WESTERVELD. Pp. 187–233; maps 4; photos 8. 1939. Tin deposits.

Form Birefringence of Nemalite. J. D. H. DONNAY. Pp. 5–15; figs. 3; tables 2. U. of Toronto Studies, Geol. Series, No. 49, 1945. Results prove existence of form birefringence in nemalite.

Matamec Lake Map-Area Saguenay County. E. W. GREIG. Pp. 29; figs. 1; tables 1; pls. 6; geol. map. Geol. Rep. 22, Dept. of Mines. Quebec, 1945. Study of geology and potential economic mineral deposits of area.

Moisie Area, Saguenay County. C. FAESSLER. Pp. 15; pls. 1; geol. map. Geol. Rep. 21, Dept. of Mines. Quebec, 1945.

Mining Industry of Province of Quebec in 1943. Pp. 157; pls. 4; figs. 2. Dept. of Mines. Quebec, 1944.

Canol Geological Investigations in the Mackenzie River Area, Northwest Territories and Yukon. G. S. HUME AND T. A. LINK. Pp. 87; figs. 16; pls. 5; maps 3. Geol. Sur. Paper 45–16. Ottawa, 1945. Price 25 cents.

Preliminary Map Bass River, Colchester and Hants Counties, Nova Scotia. L. J. WEEKS. Scale 2″ = 1 mi. Geol. Sur. Paper 45–26. Ottawa, 1945.

Map 829A Waterford, Kings and Saint Johns Counties, New Brunswick. 1″ = 1 mi. Geol. Sur. 1945.

The Upper Cretaceous, Dunvegan Formation of Northwestern Alberta and Northwestern British Columbia. F. H. MCLEARN. Pp. 5; 6 fossil pls. Geol. Sur. Paper 45–27. Ottawa, 1945. Diagnostic fossils of Dunvegan formation.

Informe Geologico y Minero de los Yacimientos de Cobre de Aroa, Estado Yaracuy. VICTOR M. LOPEZ, JOHN C. DAVEY, AND ENRIQUE RUBIO. Pp. 138; figs. 28. Caracas, Venezuela, 1945. Results of studies in 1943 on the closed copper properties of the South American Copper Co., Ltd., i.e., San Antonio, Aroa, Aroa H., Zanjon Verde, Titiara and Titiara H.; economic possibilities and sulphuric acid potentialities.

Geology of Northwestern Oregon; Oil and Gas Investigations; Prel. Map 42, 40 × 60 in. U. S. Geol. Sur. Wash., 1945. Tertiary formations in color with geologic columns and descriptive geology.

Geologic and Structure Map of Little Buffalo Basin, Oil and Gas Possibilities, Wyoming, 24 × 25. U. S. Geol. Sur., 1945. Black print showing cross sections, structure contours and wells.

Marine and Air Navigation. J. Q. Stewart and N. L. Pierce. 472 pp. quarto; illustrated. Ginn & Co., N. Y., 1945. Price $4.50. A self-contained treatise complete with all charts and necessary tables to explain in readily understandable form present-day practices and methods of air and marine navigation. Only complete treatment known; contains eight star charts; simple astronomy; excellent text book.

Physical Science. Wm. F. Ehret, editor, and L. E. Spock, W. A. Schneider, C. W. Van Merwe, and H. E. Wahlert. Pp. 638; illustrated. Macmillan Co., N. Y., 1942. Price $3.90. Text for elementary orientation course in science covering astronomy, physics, chemistry, geology, mathematics and metallurgy.

Plant Growth. L. E. Yocum. Pp. 203; pls. 16. Jaques Cattell Press, Lancaster, Pa., 1945. Price $3.00. How and why of plant growth; mostly botany; chapters on soils and fertilizers.

SOCIETY OF ECONOMIC GEOLOGISTS

THE WORK OF THE NATIONAL RESEARCH COUNCIL, DIVISION OF GEOLOGY AND GEOGRAPHY, 1944–45.

In order to avoid travel, the annual meeting of the Division was cancelled this year, but reports were submitted by the Chairman and Vice-Chairman of the Division as well as by several of the committees and were transmitted by mail to the members of the Division, including your representative, who this year serves also as a member of the Executive Committee. As distributed, the reports included those of the following geological committees: Geological Personnel, Glacial Map of North America, Tectonics, Study of Paricutin Volcano, Stratigraphy, Measurement of Geologic Time, Genetics—Paleontology—Systematics, Marine Ecology as Related to Paleontology, Paleobotany, Micropaleontology, Experimental Deformation of Rocks, Deformation of the Ross Shelf Ice, Geology of Ceramic Raw Materials, Sedimentation, Density Currents, Meteorites, Cryptovolcanic Structures, and Advising Prospective Geology Students. The following discusses the outstanding features of those reports believed to be of special interest to economic geologists and presents certain conclusions.

As described by Mr. W. W. Rubey, Chairman of the Division, two types of work have chiefly occupied geologists during the latest war year. These were: (1) the finding or conserving for wartime use of certain essential minerals and (2) advising upon, designing, or otherwise aiding in military operations. The Division itself was not called upon to participate directly in such work, but extensive assistance was furnished by geologists in government or in private life. The Division collaborated with the Office of Scientific Personnel of the National Research Council and with the Geological Society of America, the American Association of Petroleum Geologists, and the Society of Economic Geologists in facing such personnel problems as were brought to a critical pass in the profession by the war. This work included (1) the preparation of various manuals and bulletins to be published by the War Manpower Commission for use by local draft boards, employers, and returning service men; (2) participation in a study conducted by the Office of Scientific Personnel, of the civilian scientists whose studies were interrupted by the war; this latter study resulted in establishing a new group of N.R.C. pre-doctoral fellowships (see "Science," March 30, 1945).

Plans were also laid for rapidly integrating the work of the Division with the Research Board for National Security, designed to carry on military research, in case such a board is created. The Division also aided in setting up a plan whereby some of the material accumulated during the war and soon (it is hoped) to be released by the Army Map Service will be widely and yet suitably distributed in the United States.

There has been some reorganization of the geologic committees of the Division, but your representative must confess that as yet no really satisfactory plan has been devised for (1) retiring moribund committees, (2) clearly defining the purposes and terms of service of committees now active, and (3) creating new committees where needed if their functions seem, in reality or merely by name, to

overlap to any appreciable degree the activities of other committees, even though the pre-existing committees do not achieve the purposes for which the newly proposed committees are designed. During the war many committees were understandably inactive, but now they should either become palpably active and useful or should be disbanded.

Among the achievements reported by the various active committees, the following, accomplished since the publication of the last report, should be of interest to economic geologists. The Tectonic Map of the United States, designed by a divisional committee, was published by the American Association of Petroleum Geologists in November, 1944; a similarly designed Glacial Map of North America is under preparation, to be published by the Geological Society of America. (Note: this map was in engraver's proof on December 1, 1945.)

The excellent correlation charts of sedimentary formations being prepared by the Committee on Stratigraphy have now appeared in the number of eight, and more are in preparation; they are being published by the Geological Society of America and are of great value to all phases of economic geology, most especially, perhaps, to petroleum geologists.

In personnel work various government agencies have received help from the Committees on Geological Personnel and on Advising Prospective Geology Students. Such aid, together with that furnished by private critics, has brought nearly to completion and publication a manual on "Geology as a Profession," prepared by Miss Ann R. Taylor of the National Roster for Scientific and Specialized Personnel, and to be published by the government. (Note: contract for this pamphlet was scheduled to be let as of December 21, 1945.) Other committees have under way work of special interest to economic geologists: the Committee on the Geology of Ceramic Raw Materials is designing a treatise on occurrence of ceramic raw materials; the U. S. Committee for the Study of Paricutin Volcano is sponsoring, jointly with its Mexican counterpart, detailed work of interest to students of ore deposits, and pursued along the lines suggested by its name; and a Committee on Experimental Deformation of Rocks is outlining a program on rock deformation. Through the Division, a special committee on the properties and utilization of mica, organized at the request of the Office of Production Research and Development, designed an investigation which was then assigned by that office to a private research institution.

The royalties from "Ore Deposits as Related to Structural Features," having by now covered all publication costs, are henceforth being given, at the suggestion of Dr. W. H. Newhouse, Chairman of the committee of the authors of that report, to the Society of Economic Geologists for the support of the Annotated Bibliography of Economic Geology.

Space does not permit full enumeration and discussion here of all the reports rendered by the various committees. The reports themselves, contents of which are suggested by the titles given in the first paragraph of this summary, may be obtained by anyone interested through the Chairman of the Division, Mr. W. W. Rubey, National Research Council, 2101 Constitution Avenue, Washington 25, D. C.

In closing, I wish especially to remark on the effective work of Mr. Rubey, Chairman of the Division, in furthering the many worthwhile war activities that came to his desk. Throughout his term of office he played his rôle as the chief representative of our science with energy, knowledge, wisdom, and devotion.

CHAS. H. BEHRE, JR.,
Representative of the Society
on the National Research Council.

Jan. 14, 1945.

WILLARD LAWSEN CUMINGS

1874–1945.

Willard Lawsen Cumings, Chief Geologist for the Bethlehem Steel Company, died, after a brief illness, in Bethlehem, Pennsylvania, on Tuesday, May 15, 1945, at the age of seventy-one. Only two days before Mr. Cumings had entertained a group of friends at his country home near Bethlehem. Gay and humorous, he saw to it that his guests had a good time, and enjoyed doing so, with no sign of approaching illness.

Born April 26, 1874, at Sparta, Michigan, to Nelson and Adelaide Cumings (nee Stevenson), Cumings attended Michigan Agricultural College (now Michigan State College). Here he studied forestry, receiving the B.S. degree in 1882, when barely 18. He later became interested in mining and geology, and went to the Michigan College of Mines, where he obtained the degree of Engineer of Mines in 1900.

Upon graduation he was employed by the United States Steel Corporation, In 1904, while still in the service of U. S. Steel, he did special work for the Bethlehem Steel Company in Cuba. His full time employment with that company began on February 1, 1906.

During thirty-nine years' association with Bethlehem Cumings examined and reported on scores of raw materials properties. The types of materials he investigated included iron ore, coal, limestone, manganese, chromite, tin, zinc, and fluorspar. His investigations took him to various parts of the United States and Canada, Mexico, Central America, South America (especially Chile, Brazil and Venezuela), Africa, and Spain. Everywhere his lively sense of humor was a delight to his friends and business associates.

In the many years of his association with the Bethlehem Steel Company, Mr. Cumings was instrumental in the company's acquiring numerous additional properties which increased the raw material reserve materially. He was one of a small group responsible for the development of a new ore body at Cornwall, Penna., and of sizeable iron ore deposits in foreign countries.

He was a founder of the Society of Economic Geologists, a member of the American Institute of Mining and Metallurgical Engineers, the Mining Club of New York, the Canadian Institute of Mining and Metallurgy, and Tau Beta Pi.

On October 16, 1906, he married Josephine Johnson at Marquette, Michigan. They had two children, Josephine and William, both of whom are married and living in Bethlehem at present.

Mr. Cumings' many friends in the iron and steel business feel a deep loss at his passing. They remember a man who was modest despite his accomplishments as a geologist in the field of industry, a man who lived a full life, a man who, could he have planned it, would have wished to be at his work to the last full day of his life—as he was.

ARTHUR C. SPENCER.

HENRY BARNARD KUMMEL

1867–1945.

October 23, 1945, saw the passing of another of the charter members of the Society. Born May 25, 1867, in Milwaukee, Wis., Dr. Kummel received his early collegiate training at Beloit College where he was awarded the A.B. degree in 1889. After two years as instructor in the Beloit College Academy, he chose

geology as his profession and obtained his A.M. degree at Harvard while an assistant in the Geology Department. Then he held a fellowship at the University of Chicago where he received the Ph.D. in 1895.

At the University of Chicago, Dr. Kummel came under the influence of Rollin D. Salisbury, who, in 1891, had been put in charge of investigating the Pleistocene formations in New Jersey. Naturally his student found employment in New Jersey in the summer, 1892, and aided in the mapping of the glacial deposits. This employment continued seven years. During 1895–1897 Dr. Kummel completed the mapping of the Triassic formations in New Jersey, among professional geologists probably his best-known work. Appointed geologist on the staff of the Geological Survey of New Jersey in 1895, he was made Assistant State Geologist in 1899, and State Geologist in January, 1902, upon the retirement of John C. Smock. Until June 30, 1937, he served New Jersey with distinction, first as State Geologist, and from 1922 as State Geologist and Director of the Department of Conservation and Development. As director of a large state department his administrative duties were heavy, yet he found time to supervise the publication of many geologic reports, retaining an active interest in every aspect of New Jersey geology. His last publication, a labor of love following retirement, may well be the longest remembered,—a thorough revision of the 1914 report by himself and J. Volney Lewis, "The Geology of New Jersey."

Dr. Kummel was the first president of the Association of American State Geologists, and that association's representative on the National Research Council in 1937. He was a Fellow of the Geological Society of America and was honored with its vice presidency in 1931. He was also a Fellow of the American Association for the Advancement of Science. He contributed many papers to geological journals.

Dr. Kummel was devoted to his church, having served as elder of the Prospect Street Presbyterian Church in Trenton, its treasurer for 17 years, and for a period president of its board of trustees. He had many other outside interests and was a member and past president of the Torch Club.

Austere in appearance, Dr. Kummel was anything but that toward his friends and fellow workers. He could laugh at a good story with the rest, notably at tales by others of riding with him while he described the surrounding geology with eloquence and gestures, sometimes using both hands to the consternation of his passengers.

MEREDITH E. JOHNSON.

SCIENTIFIC NOTES AND NEWS

PROFESSOR CARLTON D. HULIN who has been serving as consulting geologist with the Foreign Economic Administration of the United States has resigned from that organization and has returned to the University of California. While with the Foreign Economic Administration Dr. Hulin visited India and China on a special mission involving investigaton of resources of strategic metals and minerals. In addition to university work he plans to resume private consulting practice.

RICHARD J. LUND has left the Reynolds Metal Co. as Director of Research to join the staff of the Battelle Institute, Columbus, Ohio.

HUGH MCKINSTRY has now taken up his new duties as Professor at Harvard teaching mining geology.

DAVID GALLAGHER has left for the Pacific and is assigned to military geology for the U. S. Geological Survey.

CHARLES W. WRIGHT has now left the Bureau of Mines and is associated with Ventures, Ltd., presently stationed in Washington.

ARTHUR NOTMAN has returned to New York from Malaya.

CHARLES H. BEHRE, JR., has resigned as secretary of the Society of Economic Geologists and Olaf Rove has been elected his successor.

EARL IRVING after having served with the Metals and Minerals Divisions of the F. E. A. has returned to Honduras where he will carry on geological work at the New York Honduras and Rosario Mine.

The residue of the Metals and Minerals Divisions of the F. E. A. has been absorbed by the Office of Metals Reserve of the R. F. C.

E. N. PENNEYBAKER has left for Africa to carry on extended geological work at the O'okiep Mine.

Oil has been struck at a depth of 7,200 feet in the southern tip of Chile as a result of exploration carried on under the direction of GLENN RUBEY.

A. R. KINKEL, JR., formerly in the Regional Office of the U. S. Geological Survey in Salt Lake City, is now mapping the geology of the Weaverville quadrangle, California.

PAUL FOURMARIER, who writes from the Institute de Geologie, University of Liège, Belgium, informs us that Victor Brien and Ivan de Magnee are in good health and have resumed their work. Dr. Fourmarier lost much of his personal property in the bombing of his home.

DR. QUIDO ZARUBA-PFEFFERMAN of Prague, member of the Society of Economic Geologists, is again active as a geologist in his native city and is resident at his old address. The death of Dr. Zaruba's colleague, DR. FRANTISEK ULRICH of Karlova University, is also announced. Dr. Ulrich was a member of the Society of Economic Geologists, having been elected in 1939.

HERBERT G. MOULTON has returned from Europe and is now on terminal leave as colonel in the army.

HOMER D. IRWIN, geologist, died September 10, 1945.

J. OSBORN FULLER has returned to the Geology Department of West Virginia University. He was granted leave from the University to work on the U. S. Geological Survey on a study of the only oil field in Virginia, located in the southwestern part of the state in Lee County.

C. K. LEITH, when the W.P.B. ceased to exist early in November, brought to an end five years of war service in Washington.

L. KENNETH WILSON, geologist for the American Smelting and Refining Co. and formerly stationed at Salt Lake City, has been appointed chief geologist for the Southwestern mining department, 813 Valley National Bldg., Tucson.

GEORGE C. SELFRIDGE, after two years' leave of absence spent in Government service in New York City, has returned to the University of Utah as associate professor of economic geology.

JOHN G. MCNIVEN, manager of Negus Mines, has been elected chairman of the newly organized Yellowknife Branch of the Canadian Institute of Mining and Metallurgy, the Institute's most northerly branch.

PHILIP J. SHENON, of the U. S. Bureau of Mines, who has been on an extended geological mission for the U. S. Army in the Pacific, has concluded that work and returned to his home in Spokane.

CARL TOLMAN, head of the Department of Geology, Washington University, has been elected chairman of the St. Louis section of the American Institute of Mining and Metallurgical Engineers.

THOMAS H. MURDOCK has resumed his duties as assistant geologist with the North Carolina State Department of Conservation and Development, Raleigh, N. C.

FORBES WILSON, administrative manager of Nicaro Nickel Co. at Nicaro, Cuba, for the past two years, has returned to Cuba.

SAMUEL I. BOWDITCH has resigned from the Foreign Economic Administration in Washington, where he was a mineral specialist in charge of lead, and has accepted a post as mining geologist with the American Smelting and Refining Co., with headquarters at Salt Lake City.

JOHN W. VANDERWILT, consulting geologist of Denver, has been appointed to direct a study of Colorado's mineral resources and their future potential utilization.

FRANCIS M. VAN TUYL, Professor of Geological Engineering at the Colorado School of Mines, went to São Paulo, Brazil, late in September, where he has been retained in an advisory capacity by a group of Brazilian industrialists for planning a long-term exploratory program for the development of Brazil's mineral resources.

FREDERICK P. GAETHKE, Lieutenant Colonel in the U. S. Army, has charge of all things metallic and non-metallic in American-occupied Germany.

J. L. MCMANAMY resigned as staff geologist with the Missouri Geological Survey and is now associated with C. E. Brehm, consulting geologist, with offices in the Stumpp Bldg., Mt. Vernon, Illinois.

DOAK C. COX has left the U. S. Geological Survey, for which he has been in charge of fluorspar investigations in Colorado and northwestern states for three years, to become geologist for the Hawaiian Sugar Planters Experiment Station, Honolulu.

JAMES A. MARSH, consulting geologist formerly with the mine exploration division, U. S. Bureau of Mines, has been appointed consulting geologist to the Utah State Land Board.

CLAUDE E. NEEDHAM of Washington, D. C., editor of the U. S. Bureau of Mines "Minerals Yearbook" since 1942, has been appointed supervisor of the Metals Economics Division's office at Salt Lake City.

W. RANDOLPH GREEN has been appointed geological development agent for the Great Northern Railway at Spokane.

E. W. NEWMAN, formerly in charge of the Helena office of the Bureau of Mines, is now with the American Smelting and Refining Co., Salt Lake City.

RUSSELL N. THATCHER, First Lieutenant in the Corps of Engineers, has recently returned from Europe and is again associated with the Johns-Manville Corp., of New York, as mining geologist and assistant to the vice-president in charge of exploration and mine development.

A. V. TAYLOR, JR., has resigned as mines geologist of the U. S. Smelting Refining and Mining Co., Salt Lake City, and, with an associate, plans to devote his entire time to the business of the Taylor-Knapp Co.

JOHN J. CROSTON, former assistant director of the tin, lead, and zinc division of W. P. B., now loaned by C. P. A. to the U. S. Commercial Co. (R. F. C.), has left for the Netherlands Indies on matters connected with tin.

ARTHUR D. STORKE has been appointed by the British Government to advise the Secretary of State for the Colonies on the policy of rehabilitation. He has been working on a fact-finding survey on tin in Malaya.

J. M. S. KRISHNAN, Regional Vice-President for India of the Society of Economic Geologists, states that the Geological Survey of India is resuming active publication and normal peace-time field work, both of which were curtailed or eliminated during the war due to paper shortage and war activities.

IAN CAMPBELL has returned to his position as associate professor of petrology and associate chairman of the Division of the Geological Sciences at the California Institute of Technology in Pasadena. During his leave of absence from the California Institute Dr. Campbell served as a senior training engineer and as chief of the editorial section for the University of California Division of War Research at the U. S. Navy Radio and Sound Laboratory in San Diego. For part of this period Dr. Campbell also served as a BuShips Field Engineer-Instructor and was attached to the Pacific Fleet Operational Training Command.

ALFRED WILSON has resigned from the F. E. A. and is now residing at 530 East 7th Street, Trenton, Missouri.

ROBERT K. WARNER has transferred along with the Metals and Minerals Divisions of the F. E. A. to the Office of Metals Reserve of the Reconstruction Finance Corporation in Washington.

WILLIAM E. WRATHER, Director of the U. S. Geological Survey, has gone to Mexico for a brief trip.

THOMAS MURDOCK has left the F. E. A. in Washington and is now located at the Division of Mineral Resources, Department of Conservation and Development, Raleigh, North Carolina.

RAYMOND BROOKS has written from South Africa that he is now comfortably settled at 18 Sterling Street, Waverly, Johannesburg, South Africa, and is carrying on a search for promising ore possibilities there.

A. A. MACKAY is recuperating for a few months at the Southwinds Club, Lake Placid, Florida.

DAVID SHARPSTONE has moved his headquarters from Johannesburg, South Africa, to Bulawayo, Southern Rhodesia.

PAUL KRUGER of Santiago, Chile, is temporarily in Philadelphia, and spends part time at the Nitrate Company Office at 120 Broadway, New York.

C. DEWITT SMITH has returned from the Pacific and is temporarily stationed in New York.

JAMES DOUGLAS, formerly Deputy Director for Metals and Minerals of the W. P. B., is now associated with the Phelps Dodge Corporation at 40 Wall Street, New York.

WILLIAM F. NETZEBAND, geologist for the American Zinc Lead and Smelting Company, has returned to Joplin, Missouri, after completing geological investigations at Silver City, New Mexico.

W. C. WIMER, geologist for Anaconda, has been transferred from Salt Lake City to the Company's property at Darwin, California.

G. C. MATHESRUD has been released by the Navy and has rejoined the geological staff of the Homestake Mine.

STATE COLLEGE OF AGRICULTURE AND APPLIED SCIENCE LIBRARY MAR 13 1946 MANHATTAN KANSAS